PRACTICAL PYROMETRY

THE THEORY, CALIBRATION AND USE OF IN-STRUMENTS FOR THE MEASUREMENT OF HIGH TEMPERATURES

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SECOND EDITION REVISED

PREFACE

THE day is already past when foundrymen and steel workers depend upon the eye to judge the temperatures of their product in the various stages of its heat treatment, when makers of ceramic products depend upon the indication of fusible cones, and when operators of cold storage plants are content to observe numerous thermometers scattered throughout their establishments. The requirements of modern industrial processes and the severe competition of commercial enterprises now require not only more precise knowledge of temperatures, but in many cases also require a continuous automatic record of the temperature state extending over an interval of time.

Several years ago, anticipating the need by technical students of a Course in High Temperature Measurements, the work of testing the various methods and apparatus was begun. After three years devoted to this survey, a course was organized and offered. It was received with such favor that it was made a required subject in the plan of study for students of chemical engineering at Purdue University. Each year since then, a new edition of Notes, in mimeographed form, has been put into the hands of the students. It has now been thought proper to put into more readable and permanent form the results of this experience.

In the present book, the needs of three distinct classes of readers have been kept in mind — college students, technically trained men who deal with processes requiring high temperature measurements, and less trained observers who may make the measurements. For the first two classes, who require much fuller theoretical discussions than the latter, are developed in some detail the principles involved. In some cases the discussion of these principles involve physical and mathematical ideas beyond the training of the average observer. For the less trained observer

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are given the physical principles and manipulative details with which he would require familiarity, many of which would have been omitted if the needs of only the more trained readers had been kept in mind.

At all times the publications, experience and advice of G. K. Burgess and the other members of the staff of the Bureau of Standards have been generously extended to us and freely used. We are glad to take the opportunity to thank them for their many courtesies.

All of the illustrations have been engraved especially for this book, but some of them are copies of catalogue plates of standard commercial apparatus.

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PRACTICAL PYROMETRY

CHAPTER I

STANDARD TEMPERATURE SCALES

1. The Comparison of Temperatures. — Lengths can be directly measured by means of a foot rule, a meter bar, a surveyor's chain or other standard of length. Similarly, volumes can be measured in terms of some standard of volume such as a gallon, bushel, or cubic foot. Temperatures, however, cannot be directly measured. In fact, temperatures can be compared only indirectly in terms of some property which changes in magnitude when temperature changes. For example, since when under constant pressure the length and volume of most substances increase as their temperature increases, changes of length and volume can be used for the comparison of temperatures.

Again, since the pressure of a fixed mass of gas kept at constant volume increases when the temperature of the gas is raised, changes in the pressure of a gas under these conditions can be used as a measure of the changes of temperature.

If a circuit be formed of wires of two different metals, and if the two junctions of the metals be kept at different temperatures, electromotive forces of different values are usually developed at the two junctions and in the wires between the junctions. For wires of given materials, the resultant electromotive force is a function of the difference of temperature of the two junctions. Since electromotive forces are readily measured, this thermoelectric effect can be used for the comparison of temperature differences.

Again, since the total energy radiated per second by a hot

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body increases when the temperature is increased, we might measure temperature in terms of the rate of radiation of energy from unit surface of a body.

In fact, each of the properties mentioned is employed in the comparison of temperatures. For one set of conditions a device based upon one of these properties is best suited, while under other conditions a device based upon a different property is preferable.

2. Scales of Temperature. — For the specification of a temperature we require not only a means of showing which of two bodies is at the higher temperature, but also a scheme for indicating numerically the amount that the temperature of one body exceeds that of the other. That is, we must have a scale of temperature.

Any one of the properties of matter previously mentioned can be used as a basis for the construction of a temperature scale. For instance, if at a certain temperature the length of a given copper rod is midway between the length of the same rod when at the temperature of melting ice and that of the steam from boiling water, we might say that the certain temperature is midway between the temperature of the melting ice and that of the steam from boiling water. Then, if the temperature of melting ice be denoted by zero, and the temperature of steam from boiling water by 100, the certain temperature would be 50. We might go further and call those temperature differences equal that produce equal differences in the length of a copper rod. We would then have a temperature scale based on the expansion of copper.

Similarly, if we were to call those temperature changes equal which produce equal changes in the pressure of a fixed mass of a certain gas kept at constant volume, we would have a temperature scale based on a different property of matter.

In the same manner, by calling those differences of temperature equal that produce equal differences in the resistance of a wire made of given material, we could construct a different temperature scale.

But if we define equal increments of temperature in terms of

equal increments of length of a copper rod, we are no longer at liberty to call those increments of temperature equal which produce equal increments of the pressure of a fixed mass of gas kept at constant volume; nor those increments of temperature which produce equal increments of electric resistance; nor those increments of temperature which produce equal increments of any other property of matter. Indeed, we find that any one of the methods of defining equal increments of temperature leads to increments of temperature which would not be equal if any of the other methods of definition had been adopted.

3. The Centigrade and the Fahrenheit Degrees. — In the construction of any temperature scale, two definite temperatures are required, and definite numerical values must be assigned to those temperatures. The particular temperatures selected, as well as the particular numbers employed to designate these temperatures, are matters of arbitrary convention. But in order that readings made from different thermometers may be comparable, physicists have agreed upon two particular temperatures for the two fixed points. For one is taken the temperature of melting ice, and for the other, the temperature of the steam from boiling water — both under a barometric pressure of 76 centimeters of mercury.

Celsius assigned the number 0 to the temperature of melting ice, and 100 to the temperature of steam rising from boiling water. As there are 100 degrees between the two fixed points, this scale is usually called the *centigrade* scale. One centigrade degree is one hundreth of the temperature interval between the temperature of melting ice and the temperature of steam rising from boiling water.

Fahrenheit assigned the number 32 to the temperature of melting ice, and 212 to the temperature of steam rising from boiling water. Since on the Fahrenheit scale there are 180 degrees between the two fixed points, and on the centigrade scale there are 100 degrees between the same points, one Fahrenheit degree represents five-ninths of the temperature interval represented by one centigrade degree.

Thus, in Fig. 1 let *PR* represent the temperature interval between the two fixed points of the centigrade scale, and *XZ* the
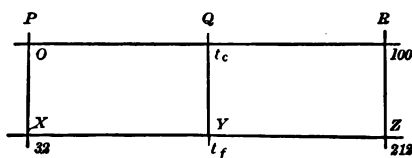
FIG. 1.

same interval on the Fahrenheit scale. A given temperature would be represented according to the centigrade scale by t_c and and according to the Fahrenheit scale by t_f.

Now
$$\frac{PQ}{XY} = \frac{PR}{XZ},$$

or
$$\frac{t_c}{t_f - 32} = \frac{100}{212 - 32} = \frac{5}{9},$$

whence
$$t_c = \tfrac{5}{9}\,(t_f - 32) \tag{1}$$

and
$$t_f = \tfrac{9}{5}\,t_c + 32. \tag{2}$$

4. The Thermodynamic Temperature Scale. — A particular property of a particular substance might be arbitrarily adopted as a standard of comparison, as for example, the relative expansion of mercury in glass, or the change of resistance of platinum. But it is highly desirable to have a standard temperature scale that is independent of the substance employed.

Carnot discovered that in the case of a reversible thermodynamic engine, the ratio between the quantity of heat absorbed and the quantity of heat emitted is independent of the working substance and depends only upon the temperatures between which the engine is operating. Lord Kelvin has shown that this fact can be utilized in the construction of a temperature scale that is independent of the medium employed.

According to the Thermodynamic Temperature Scale, the ratio between two temperatures equals the ratio between the quantity of heat that would be absorbed and the quantity that would be emitted by a reversible thermodynamic engine working between the given temperatures.

The zero of the thermodynamic scale is the temperature which the exhaust of a reversible engine would need to have in order that the engine convert into work all the heat supplied to it. It is the temperature at which the working substance is devoid of heat. For this reason, the thermodynamic zero is usually called the *absolute* zero of temperature. It is found that the temperature of melting ice expressed in centigrade degrees on the thermodynamic scale is about 273.7° C.

If, when two bodies are in contact and shielded from outside thermal disturbance neither body gains or loses heat, the two bodies are said to be in thermal equilibrium with one another. According to the thermodynamic temperature scale, two bodies in thermal equilibrium are at the same temperature.

5. The Ideal Gas Temperature Scale. — All gases obey the laws of Boyle and Charles for limited ranges of pressures and temperatures. For these ranges gases are said to be "ideal" or "perfect." The properties of perfect gases are so simple and their departure from the properties of actual gases are so readily obtained that they occupy an important place in physics.

From the fundamental law of perfect gases,

$$pv = RmT,$$

it follows that by reckoning temperatures from a point about 273.7 centigrade degrees below the melting point of ice, the temperature of a fixed mass of perfect gas at constant volume varies directly with the pressure. This furnishes an "ideal gas" temperature scale. *According to the Ideal Gas Temperature Scale, the ratio between two temperatures equals the ratio between the pressures of a fixed mass of ideal gas at constant volume when at the given temperatures.*

It can be shown theoretically that temperatures expressed

according to the Ideal Gas Scale are represented by the same numbers when expressed on the Thermodynamic Scale.

Bodies that are in thermal equilibrium with one another are at the same Ideal Gas Temperature.

After determining the departure of the properties of an actual gas from the properties of an ideal gas, an actual gas can be used as the thermometric substance and the results reduced to the ideal gas temperature scale. The particular gas selected to be the standard thermometric substance should be one that can be readily obtained at any time or place, and whose physical character does not alter throughout a wide range of pressures and temperatures. Hydrogen fulfills these requirements and has been adopted as the standard thermometric substance.
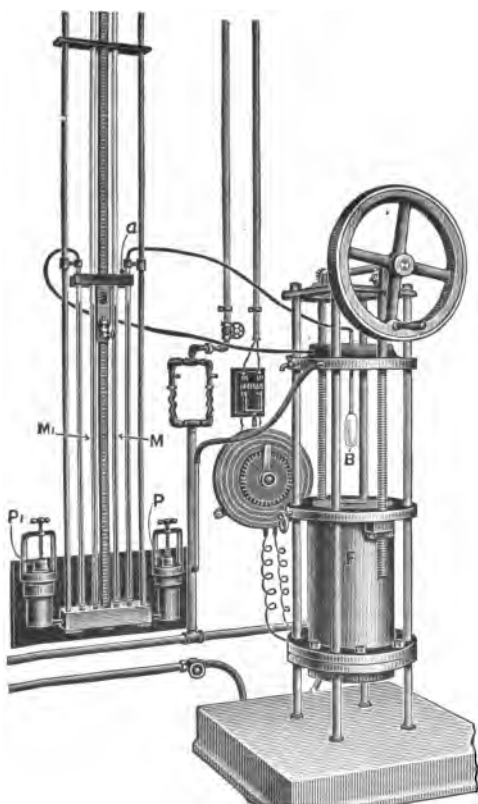
FIG. 2.

6. The Normal Thermometer, adopted as the standard instrument for the comparison of temperatures according to the Ideal Gas Temperature Scale, is a constant volume hydrogen thermometer with the gas under a pressure of 1000 mm. of mercury at the temperature of melting ice. On account of the danger of the hydrogen diffusing through the material of the bulb at high temperatures,

the normal thermometer is seldom used above 300° C. From temperatures from 300° C. to 1550° C. the constant volume nitrogen thermometer is more reliable than the normal thermometer. In practice, however, the gas thermometer is employed only to standardize some form of instrument that is easier to operate.

Only at temperatures above 1000° C. is the departure of the Normal Hydrogen Scale so much as one degree centigrade from the Ideal Gas Scale. When necessary, the proper correction can be made.

The normal thermometer in the Physics Laboratory of Purdue University is illustrated in Fig. 2. It consists of a bulb B, made of either quartz or an alloy of platinum and rhodium. The capillary stem is joined to the open manometer M. The bulb is enclosed in an electrically heated furnace F, which is protected from outside thermal disturbances by means of a water jacket through which flows a steady stream of water.

By adjusting the plunger P so that the mercury in the manometer M is maintained at the fiducial mark a the volume of the gas in the bulb is kept at a definite value.

The bulb and the furnace are filled with either hydrogen or nitrogen. If the pressure of the gas inside the bulb were different from the outside, there would be danger of a change of volume of the bulb. By means of the plunger P_1 and manometer M_1, the pressure of the gas outside the bulb is maintained equal to that inside.

There is no actual temperature-measuring instrument whose action is based upon the principle of the thermodynamic scale. But experiments upon hydrogen and nitrogen, together with the properties of the thermodynamic scale, show that throughout a wide range of temperatures the indications of a constant volume thermometer in which these gases are employed give very nearly thermodynamic temperatures. The corrections to be applied at various temperatures as determined by Callendar are as follows:

Temp., ° C.	Hydrogen, ° C.	Nitrogen, ° C.
− 100	+0.005	+0.080
0	+0.000	+0.000
+ 200	+0.0024	+0.035
+ 450	+0.013	+0.189
+1000	+0.044	+0.646

7. The Black-body Temperature Scale. — Any body at a temperature above the absolute zero radiates energy at a rate which depends only upon the temperature of the body and upon the nature of its surface. If the nature of the surface is constant, the temperatures of bodies can be compared in terms of their radiance.

Experience shows that the rate at which a surface radiates, due to purely thermal causes, is proportional to the rate at which it absorbs the same kind of energy. That is, a perfect absorber would be a perfect radiator. A body that absorbs all the radiance incident upon it — not reflecting any or transmitting any — is called a *black-body*. A black-body is a perfect radiator, and all black-bodies at the same temperature radiate at the same rate. It follows that the temperature of black-bodies can be compared by means of their thermal radiation.

It has been shown by Stefan and Boltzmann that the rate with which energy due to thermal causes is radiated by a black-body is proportional to the fourth power of the thermodynamic temperature. This furnishes a means of determining the thermodynamic temperatures of black-bodies which may be either inaccessible, or so hot that an instrument could not safely be placed in contact with them.

If the body be nonblack, the rate with which energy is radiated will not be proportional to the fourth power of the temperature according to the thermodynamic scale. But we can construct a scale such that the fourth power of the temperature according to this new scale shall be proportional to the rate with which energy is radiated by the body. This so-called Black-body Temperature Scale is of great importance in expressing tem-

peratures of bodies that are either inaccessible or too hot for an instrument to be placed in contact. *According to the Black-body Temperature Scale, when the energy radiated from two surfaces is due to purely thermal causes, the ratio between the temperatures of these surfaces equals the fourth root of the ratio between the rates of radiation per unit area from the surfaces.*

Two bodies will be at the same black-body temperature when the rate of their radiation per unit surface is the same. In the present and succeeding pages only radiance due to purely thermal causes is considered. Radiance due to chemical or luminescent causes is excluded.

A piece of retort carbon absorbs almost all of the radiance, of whatever frequency, incident upon it. Consequently retort carbon is nearly black. A piece of polished platinum absorbs partially, but to practically the same extent, radiance of all frequencies. Consequently polished platinum is gray. A lump of gold absorbs nearly all the radiance incident upon it with the exception of the waves that produce the visual sensation we call yellow. This selective absorption of gold is described by the statement that gold is yellow. If pieces of retort carbon, polished platinum and gold be placed together within a uniformly heated enclosure until they are in thermal equilibrium and be then withdrawn, it will be found that the carbon will radiate at a greater rate than the platinum or gold. That is, although all three bodies are at the same temperature according to either the thermodynamic or the ideal gas scales, they are at different black-body temperatures.

Bodies, either black or nonblack, emitting radiance per unit area at the same rate are at the same black-body temperature: and if they are in thermal equilibrium with one another they are at a common thermodynamic temperature. In the case of a black-body the same number that expresses its thermodynamic temperature also expresses its black-body temperature. But since a nonblack body at the given thermodynamic temperature radiates less than a black-body at the same thermodynamic temperature, the number which expresses the black-body tem-

perature of a nonblack-body is less than the number which expresses its thermodynamic temperature.

8. The Application of the Three Standard Temperature Scales. — To meet various specific industrial requirements, thermometers have been devised and are in successful use that depend upon the expansion of one metal relative to another, the relative expansion of a liquid and the containing tube, the resistance of a wire, the change in electromotive force developed by heat, the rate of emission of radiant energy by the hot body, the brightness of the luminous energy of a selected wave length emitted by the heated body. But for any work of precision, a thermometer of any type is calibrated in terms of the normal thermometer. This instrument has been adopted as the standard thermometer. But on account of its size and the care required in its operation, it is not used in industrial processes, but only for the calibration of more convenient instruments. The normal thermometer indications can be reduced to the ideal gas temperature scale.

In work of precision all temperatures are expressed according to the thermodynamic temperature scale. There is no thermometer whose action is based upon the principle of this scale. But it can be shown that the thermodynamic scale is identical with the ideal gas scale. Now any thermometer that can be placed in contact with the bodies whose temperatures are sought, and remain till it is in thermal equilibrium with its surroundings, can be calibrated directly with a normal thermometer and the indicated temperatures reduced to the ideal gas temperature scale. These ideal gas temperatures equal the thermodynamic temperatures.

In many cases, however, due either to the inaccessibility or high temperature of a body, a thermometer cannot be brought into thermal equilibrium with the body whose temperature is sought. Recourse must then be had to the energy radiated by the body and received by a suitable measuring instrument. Let such an instrument be directed toward a black-body that can be raised to a series of known thermodynamic temperatures.

From a series of readings of the instrument corresponding to known thermodynamic temperatures of the hot body, a calibration curve for the instrument can be constructed. This curve will give the thermodynamic temperature corresponding to any reading of the instrument within the range of the calibration when the instrument is directed toward a black-body. When the instrument is directed toward a nonblack-body, the same calibration curve will give, not thermodynamic temperatures, but black-body temperatures.

Since a nonblack-body radiates at a less rate than a black-body, it follows that the number which represents any temperature according to the black-body scale is smaller than the number which represents the same temperature on the thermodynamic scale. The difference between the two numbers depends upon the departure of the radiation of the given body from that of a black-body. This departure is a matter of the surface of the body. If the radiation coefficient of the surface be known, the thermodynamic temperature corresponding to any black-body temperature can be determined. In few cases, unfortunately, is the radiation coefficient available. From black-body temperatures of two bodies of unknown radiation coefficients we can infer little with regard to the relative thermodynamic temperatures of the bodies. For example, when a specimen of carbon and one of platinum are at the same black-body temperature 1500° C., the thermodynamic temperature of platinum will be about 180° C. greater than that of the carbon.

CHAPTER II

RESISTANCE PYROMETRY

9. Relation Between Resistance and Temperature. — Since the electrical resistance of most metals varies continuously with the temperature according to definite laws, and since the accurate measurement of resistance is attended with no considerable difficulty, thermometers depending upon this property are in common use for measuring high and low temperatures. To be available for such use, the metal must have always the same resistivity when at the same temperature, and its temperature-resistance coefficient should be large. Platinum may be used from the lowest temperatures up to 1100° C. For temperatures below 200° C. pure nickel is usually employed.

It has been shown by experiment that if R_0 represent the resistance of a piece of pure platinum or of pure nickel or of certain other metals, when at 0° C., then the resistance at $t°$ C., is expressible by the equation:

$$R_t = R_0 (1 + at + bt^2). \qquad (3)$$

when a and b are constant quantities. These three constants can be determined from the resistance of the wire at three known temperatures.

10. The Wheatstone Bridge. — It is easily shown that in the case of a circuit containing resistances R_1, R_2, R_3, and R_4, joined to a battery and galvanometer as represented in Fig. 3, there is no current in the galvanometer when

$$\frac{R_1}{R_2} = \frac{R_3}{R_4}. \qquad (4)$$

Thus, if any three of the resistances are known, then when no current flows through the galvanometer, the remaining unknown

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resistance can be determined.   This is the most common method of measuring resistances.

For general resistance measurements, a Wheatstone bridge having three groups of coils of known resistances, with convenient arrangements for altering the resist-
ance of each group, is usually em-
ployed.   For laboratory use, the box containing the coils is separate from the galvanometer and battery.   For shop use where portability is essen-
tial, the coils, the galvanometer and battery are enclosed in a single box. In the arrangement of the tops of
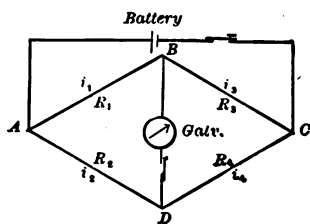
FIG. 3.

the boxes of coils there is great variety.   In some, the resistances are changed by means of plugs, and in others by means of sliding switches.   The top of a common form of cheap box of coils is shown in Fig. 4.   The lettering on this plan corresponds with that
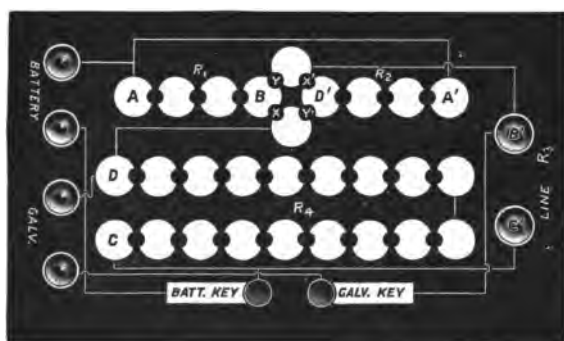
FIG. 4.

in the diagrams Figs. 3 and 5.   In this model, when there is balance with the gaps Y and Y' filled by plugs, and the gaps X and X' open, we have

$$\frac{R_1}{R_2} = \frac{R_3}{R_4},$$

whereas with the gaps Y and Y' open, and the gaps X and X' filled by plugs, the resistances R_1 and R_2 will be interchanged so that

$$\frac{R_2}{R_1} = \frac{R_3}{R_4}.$$

By this switching device the box requires two less coils than otherwise would be needed.
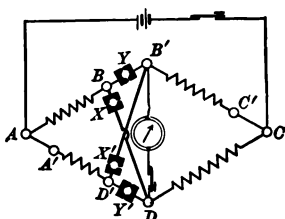
FIG. 5.
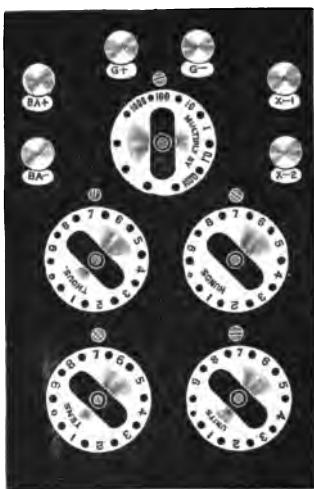
FIG. 6.

The plan of a box top in which rotating switches are used instead of plugs is shown in Fig. 6.

11. Direct Reading Resistance Pyrometers. — One of the many forms of self-contained Wheatstone bridge designed to give temperatures without computation, from a single setting, is illustrated in Fig. 7 and Fig. 8. In this device the resistance of the arms AD and DC are equal and fixed in value. The terminals m, n, and C of the lead wires from the pyrometer coil are connected into the bridge as shown. The lead wires Bm, Bn, and pC are made of the same material as the pyrometer coil Bp, and the resistances of Bm and pC are equal. The resistance of the arm of the bridge containing the lead wire mB can be continuously varied by rotating the contact arm qs over the circle of wire oqx.
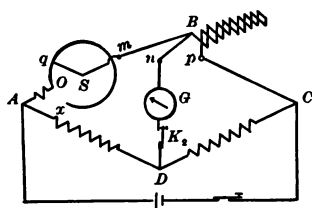
FIG. 7.

Suppose that when the contact point q is at o, the bridge is in balance. When the pyrometer coil rises in temperature its resistance will increase, and to produce a new balance the contact arm must be rotated in the clockwise direction. The circle can be divided into spaces and so marked that when the bridge is in balance, the contact arm will point to the number that indicates the temperature of the resistance bulb.

FIG. 8.

For example, suppose an instrument is to be made that shall indicate directly temperatures from 0° C. to 200° C. In this case the resistance of the coil Ao is made such that when the contact point q coincides with o, the resistance of the bridge arm AB equals the resistance of the bridge arm BC when the pyrometer bulb is at 0° C., and the resistance of the circle of wire oqx equals the increase in the resistance of the pyrometer coil at 200° C. over its resistance at 0° C. As the change in the resistance of the pyrometer coil is not directly proportional to the change of temperatures, the spaces between marks on the circular scale that indicate equal temperature intervals will not be equal.

12. The Availability of Resistance Pyrometers to Industrial Use. — In the hands of trained observers the platinum resistance pyrometer is capable of a precision within one degree centigrade from the lowest temperatures up to 900° C. This is superior to the precision obtainable by any other type of pyrometer. But such precision should not be expected of resistance pyrometers

manufactured for industrial use, especially in the hands of ordinary observers.

To avoid strains within the resistance coil, the pyrometer bulb should be installed so as to hang vertically and be free from danger of mechanical injury. The coil must be protected from furnace gases by an impervious bulb. The indicator should be as carefully treated as a clock or other instrument of equal delicacy.

The outfit should be frequently tested. It is not safe to assume that when received from the maker the scale gives correct indications, nor that the indicators will remain constant throughout any extended period of time. For instruments having a range from 0° C. to 200° or 300° C., it will usually be sufficient to check two points only: for example, the 0° C. and the 100° C. point by means of melting ice and the steam from boiling water under a barometric pressure of 76 cm. of mercury. Subsequent testing is facilitated by the use of a set of coils that have resistances equal to that of the pyrometer coil at various temperatures. For example, at the temperature of melting ice the checking coils might have the same resistance as the pyrometer coil when at 0°, 50°, 100°, etc., respectively. Then on substituting for the pyrometer coil one of the checking coils, the pyrometer indicator should point to the number marked on the checking coil.

The resistance pyrometer is especially adapted to the measurement of temperatures with considerable precision that vary through narrow limits, in situations where the pyrometer bulb is in little danger from mechanical injury. The causes which have thus far limited the use of the instrument are the fragility of the pyrometer resistance coil and the rather complicated indicating device. In cases in which the required degree of precision is not better than 10° C., the base metal thermoelectric pyrometer would be selected. While in cases in which the "fire end" can be shielded from mechanical danger and the degree of precision must be better than 10° C., the resistance pyrometer would be selected.

13. Recording Resistance Pyrometers. — By arranging a Wheatstone bridge so that changes in the resistance of a pyrometer coil produce proportional changes in the position of some part of

the apparatus which are automatically marked at regular intervals of time on a piece of paper, a permanent record can be produced of the temperatures of the pyrometer coil at different instants throughout an extended period. One successful instrument of this type, designed by the Leeds and Northrup Co., will now be described.

The bridge net includes the pyrometer coil R_3, Fig. 9, and the coils of fixed resistance Bx, yz, and dC, together with two slide-wire resistances xy and zd. On these slide-wires move the contact arms OA and OD. These contact arms are connected rigidly so that they move as a unit. The diameters of the slide wires and the resistances of the coils connected to them are such that the resistance R_2 between the slide contacts A and D always equals the resistance R_1 between A and B. With R_1 always equal to R_2 whatever the position of the sliding contacts, it follows that the galvanometer will give zero deflection when the resistance R_4 between D and C equals the resistance R_3 of the arm BC containing the pyrometer coil. Then, if with the pyrometer coil at any selected temperature the bridge is in balance when the contact D is at D', any subsequent change in the temperature of the pyrometer coil will be measured by the angle $D'OD$ through which the contact arm OD must be moved to reattain a balance. It remains to describe the device for automatically rotating the contact arms the proper amount to bring the galvanometer to the zero position, and the device for automatically recording this amount.
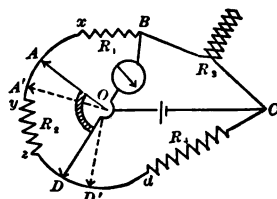
By means of a wheel A, Fig. 10, the shaft of which is connected to the contact arms OA and OD, Fig. 9, the Wheatstone bridge can be brought to balance. The direction and the amount of rotation of the wheel A is regulated by the position of the clutch arm BB' with reference to the cams C and C' on the motor-driven shaft DD'.

For example, with the clutch arm engaged with the wheel in the position shown in Fig. 10, the rotation of the cam C' will cause the

wheel to rotate a certain amount in the clockwise direction, thereby producing an equal change in the position of the contact arms of the Wheatstone bridge. The clutch arm BB' connected to the rocker arm E, is brought into engagement with the wheel A, and released, once in every revolution of the cam F on the
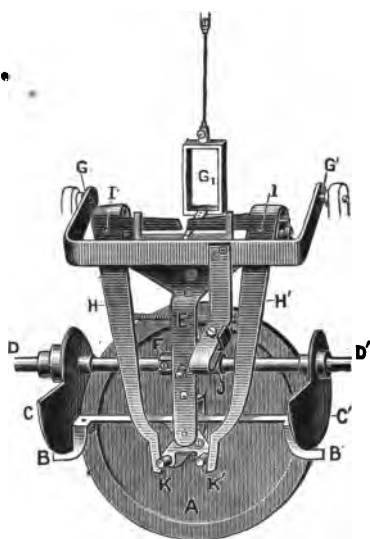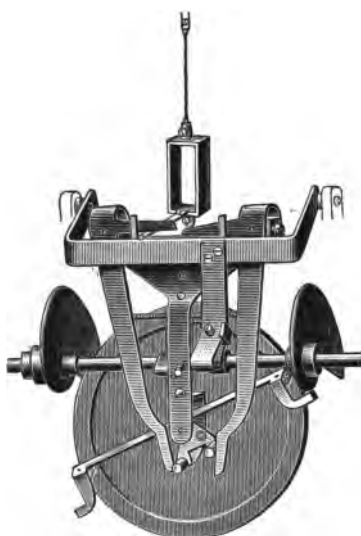
FIG. 10.   FIG. 11.

motor-driven shaft DD'. The position of the clutch arm is determined by the lack of balance of the Wheatstone bridge. When the bridge is balanced, that is, when there is zero current in the suspended galvanometer coil G, the galvanometer pointer lies directly below the gap between the ends of the right-angle pieces H and H' pivoted at I and I' respectively. When the bridge is out of balance, there is a current in the galvanometer, and the galvanometer pointer lies somewhere between the rocker E and the two right-angle pieces H and H'. Once during each revolution of the motor-driven shaft DD', the cam J raises the rocker E. If, at that instant the Wheatstone bridge is not in balance, that is, if the galvanometer pointer is not below the gap between H and H',

the rocker E will push the galvanometer pointer against the horizontal position of one of the right-angle pieces H or H'. Being pivoted at I and I', the vertical position of the disturbed right-angle piece will push against the pin K or K' and the clutch arm will be displaced as shown in Fig. 11. The amount of displacement of the clutch arm depends upon the distance between the galvanometer needle and the pivot of the right-angle piece, that is, upon the amount of lack of balance of the bridge. The direction of displacement depends upon the direction of the galvanometer deflection.
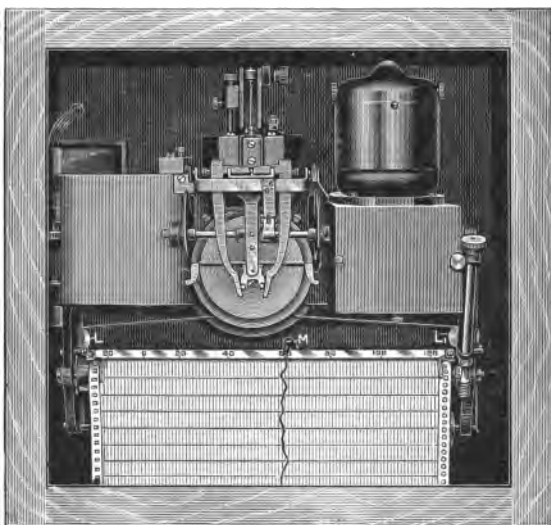
FIG. 12.

The angular displacements of the wheel necessary to rebalance the Wheatstone bridge can be transformed into linear displacements by means of a cord wrapped about two pulleys L and L', Fig. 12. A pen M attached to this cord follows the variations of the resistance, and hence the temperature of the pyrometer coil. The paper under the pen is drawn along at a uniform rate by means of clockwork. Thus the pen automatically traces on the paper a curve coordinating the temperature of the pyrometer coil and time.

By substituting a type wheel and ink ribbon for the pen, and adding a motor driven multiple point switch, the instrument just described may be arranged to record the temperatures of several different pyrometer coils. When the switch has brought the galvanometer into connection with pyrometer coil No. 1, the type wheel turns a "1" toward the paper and stamps on the paper a dot with a figure "1" beside it. One minute later the switch connects the galvanometer to pyrometer coil No. 2, the type wheel turns a "2" toward the paper and stamps on the paper a dot with a figure "2" beside it. After a record has been made of the temperatures of all the pyrometer coils, the cycle is repeated. The record for pyrometer coil No. 1, consists of a series of dots with a figure "1" alongside of each dot. The record for pyrometer coil No. 2 consists of a series of dots with a "2" alongside of each dot, and so on. If the multiple switch is arranged for eight pyrometer coils, eight minutes will elapse between successive points on the curve for any given pyrometer coil. It thus appears that this multiple record is not available for recording rapid variations of temperature.

Exp. 1. Calibration of a Resistance Pyrometer

THEORY OF THE EXPERIMENT. — Read Arts (9–10). The object of this experiment is to construct a calibration curve coordinating temperatures and resistances of a resistance pyrometer from experimentally determined values of the resistance at three known temperatures. A calibration extending from 0° C. to about 450° C., may be made from the freezing point of water and the well-known boiling points of easily obtained substances.

Substances.	Boiling points at 76 cm. Hg.
Water......................................	100° C.
Naphthalene................................	219° C.
Benzophenone..............................	306° C.
Sulphur....................................	445° C.

If the resistance of a wire at temperatures $t_1°$ C., $t_2°$ C., and $t_3°$ C., be R_1, R_2, and R_3, respectively, then we may write (3),

$$R_1 = R_0 (1 + at_1 + bt_1{}^2),$$
$$R_2 = R_0 (1 + at_2 + bt_2{}^2),$$
$$R_3 = R_0 (1 + at_3 + bt_3{}^2).$$

Knowing the three resistances R_1, R_2, and R_3 of the wire at temperatures t_1, t_2, and t_3, respectively, the constants R_0, a and b can be determined. After substituting the values of the three constants in (3) the equation thereby obtained can be used for the computation of values of R corresponding to any assumed temperatures. From a series of values of resistances and corresponding temperatures, a curve can be plotted. This will be the required calibration curve of the particular resistance pyrometer under investigation.

MANIPULATION. — The resistance pyrometer consists of a coil of fine wire enclosed in a suitable bulb, with lead wires joined to binding posts on the outside of the bulb. To eliminate any error due to uncertainty regarding the temperature of the lead wires, provision must be made to obtain the resistance of the coil alone. For example, the coil may be arranged as in Fig. 13, with a "dummy lead," mB,

FIG. 13.

joined to one end of the coil. The three leads nB, mB, Cp, are of the same length, material, and resistance. The resistance of the coil alone can be obtained by subtracting from the resistance between n and C, the resistance between m and n.

Fill a small can with pieces of ice no larger than a pea, and cover the ice with water. Immerse the resistance pyrometer bulb in this bath of melting ice.

Connect the galvanic cell, galvanometer and unknown resistance to the Wheatstone bridge, using short thick wires to connect the unknown resistance. First, with the ratio arms equal, adjust the rheostat arm until the galvanometer gives the minimum deflection on closing the battery key and then the galvanometer key. This adjustment is complete when, on changing the resistance of the rheostat arm by one ohm in one direction the gal-

vanometer deflection is increased, while on changing the resistance by one ohm in the other direction the galvanometer deflection is reversed. From the values of the resistances of the rheostat and ratio arms, the approximate resistance of the specimen can be determined by (4). Knowing the approximate value of the resistance, determine the setting of the ratio arms that will make the rheostat arm read to four digits and find the more accurate value of the resistance.

FIG. 14.   FIG. 15.

Proceeding in the same manner find the resistance of the coil when in the steam from boiling water under atmospheric pressure, and also when in the vapor from sulphur boiling under the same barometric pressure. In making these resistance measurements one must press the keys for the shortest possible time else the resistance coil will be appreciably heated by the passage of the current.

To obtain the boiling point of water a vessel such as is illustrated in Fig. 14 is very satisfactory. By means of the water manometer M, any difference of pressure between the steam inside and the air outside can be observed. If the barometric pressure be

H millimeters of mercury and the manometer indicates a pressure of d millimeters of water, or $(d \div 13.6)$ millimeters of mercury, then the total pressure on the surface of the boiling water is $H + (d \div 13.6)$ millimeters of mercury. The temperature of the vapor of water boiling under various pressures is given in Table 1.

To obtain the boiling point of sulphur the apparatus illustrated in Fig. 15 is convenient. The sulphur is contained in an aluminium tube heated by a current-carrying conductor. To prevent drops of liquid sulphur that condense on the upper part of the pyrometer tube from running down over the bulb, as well as to diminish the loss of heat by radiation, the pyrometer bulb is enclosed in a thin aluminium shield.

If the pyrometer bulb be of quartz or porcelain it will require considerable time for the coil to attain the temperature of the ice, steam or sulphur vapor. After the bulb has been immersed, take resistance readings till they remain constant for five minutes. These constant values are the ones to be used in the computation.

From the values of the three resistances determined at the three known temperatures, compute the three constants in (3). Substitute the values of these three constants in (3), and by means of the empirical equation thereby obtained, compute the resistances of the coil at various temperatures at 100° intervals throughout the range the pyrometer is to be employed. With these values of temperature as abscissas, and resistances as ordinates, plot the calibration curve of the given resistance pyrometer.

CHAPTER III

THERMOELECTRIC PYROMETRY

14. The Seebeck Effect. — Seebeck discovered that a junction of two dissimilar metals is the seat of an electromotive force. A complete circuit consisting of wires of two dissimilar metals contains two junctions and two opposing electromotive forces. If the entire circuit is at the same temperature the electromotive forces at the two junctions will be equal and opposite, whereas if one junction is at a higher temperature than the other there will be a resultant electromotive force which will cause a current in the circuit. The magnitude of the resultant electromotive force depends upon three factors:

(a) The nature of the metals;
(b) The difference of temperature of the two junctions;
(c) The actual temperature of the two junctions.

As an example of the dependence of the resultant electromotive force upon the nature of the metals, measurements show that with the cold junction at 0° C., and the hot junction at 100° C., thermoelements consisting of one wire of pure platinum and the other of the following substances develop electromotive forces as given below:

	Microvolts.*
Iron......................................	2100
Hard steel.................................	1800
Nickel steel (0.05 Ni)	0
Nickel steel (0.035 Ni)	−2700
Nickel steel (0.75 Ni)	−3700
Nickel......................................	2200

* Micro = millionth.

As an example of the dependence of the resultant electromotive force upon the difference of temperature of the two junctions,

measurements show that in the case of a thermoelement consisting of platinum and an alloy of platinum with 10 per cent rhodium, with one junction maintained at 0° C., there will be developed the following electromotive forces when the other junction has the temperature assigned.

° C.	Microvolts.
400	3,240
600	5,210
800	7,320
1000	9,570
1200	11,950
1400	14,460
1600	17,110

That the resultant electromotive force depends not only upon the difference of temperature of the junctions but also depends upon .the actual temperature of the two junctions can be illustrated by the following experiment.   Let the two ends of an iron wire be joined by copper wires to a suitable voltmeter.   Let one copper-iron junction be maintained at 0° C., while the other is gradually raised in temperature to 600° C., or more.   The voltmeter will indicate an electromotive force which increases till the hot junction is about 275° C.   When the hotter junction passes this temperature the electromotive force decreases.   This phenomenon is called *thermoelectric inversion,* and the point of inversion is called the *neutral temperature.*   When the temperature of the hot junction becomes about 550° C., the resultant electromotive force becomes zero.   On increasing the temperature above this value the magnitude of the resultant electromotive force increases in the reverse direction.   When one junction is at a temperature as much above the neutral temperature as the temperature of the other junction is below it, the resultant electromotive force is zero.

It is probable that thermoelectric couples of all elements have neutral points, though in many cases they are outside the range of temperatures of ordinary experiment.

15. Application to Temperature Measurement. — Since the resultant electromotive force of a thermoelectric couple is a .

function of temperature, temperatures can be compared by means of thermoelectric couples. A *thermoelectric pyrometer* consists of a thermoelectric couple together with some device for measuring electromotive force. Electromotive forces are accurately compared by means of a potentiometer, but are much more conveniently compared by means of a millivoltmeter. As millivoltmeters of sufficient accuracy for all industrial requirements can be easily obtained and can be calibrated so as to indicate temperature directly, potentiometers are less often employed.

A thermoelectric pyrometer should meet the following requirements:

(*a*) The resultant electromotive force developed by the thermoelectric couple should increase with rise of temperature according to a known law. A couple that produces an electromotive force which varies directly with temperature difference of its junctions would be most desirable.

(*b*) The materials composing the thermoelectric couple must be chemically and physically homogeneous, and must be chemically and physically unaltered under the conditions of use.

(*c*) In case a millivoltmeter indicator is used, the temperature-resistance coefficient of the materials composing the couple should be small. Otherwise the "immersion error" due to a change of resistance with change of temperature of the couple will be appreciable. This immersion error is obviated by the use of a potentiometer indicator instead of a millivoltmeter.

(*d*) The voltmeter should have a nearly uniform scale and sufficient sensitiveness.

(*e*) The resistance of the voltmeter compared to that of the couple and leads must be so great that the indications will not be appreciably altered by whatever fluctuations may occur in the resistance of the circuit.

(*f*) The wires composing the couple and the leads must be of sufficiently small cross section to prevent the junction being appreciably cooled by conduction of heat from it.

16. Choice of Metals for Thermoelectric Couples. — The limit of the ratio of the electromotive force developed by a couple

to the difference of temperature of its two junctions is called the *thermoelectric power* of the couple. It is usually expressed in microvolts per degree centigrade.

Many metals undergo a molecular transformation within certain ranges of temperature. Within these temperature limits such a metal is not available for use in a thermoelectric couple. For instance, nickel undergoes a molecular transformation between 230° C. and 390° C. which causes its thermoelectric power and also its resistance to depart throughout this interval from the normal trend. Nickel may be used in a thermoelectric element from 400° C., to 900° C.

A wire that is ununiformly hard throughout its length will produce parasitic currents when uniformly heated. Careful annealing will correct this fault. Wires of iron, nickel, palladium, and their alloys when heated to certain temperatures give rise to parasitic currents which render them unfit, at these temperatures, for use in thermoelectric elements.

At about 700° C., iron, steel, nickel, and copper become so brittle as to render their use inconvenient above this temperature.

As the metals of the platinum group can be heated above 1400° C. without melting, and they have no neutral temperature within the range of ordinary experiment, and as their alloys can be made physically and chemically homogeneous, these metals were early used for the construction of thermoelectric pyrometers. Care must be exercised, however, not to keep them long at a temperature above 1100° C., or they will become crystalline and brittle. And care must be taken that they be not heated in a space containing volatile metals, or their chemical composition will be altered, thereby changing their thermoelectric power. With proper precautions a thermoelectric element consisting of a pure platinum wire in connection with a wire of an alloy of platinum with ten per cent rhodium, is thoroughly satisfactory for measuring temperatures from the lowest obtainable up to about 1400° C.

The great cost of platinum and rhodium, however, has limited the adoption of the (Pt — .90 Pt .10 Rh) element for industrial

use. Much research has been devoted to the discovery of alloys of cheaper metals that would be suited to industrial measurements. Many so-called "base metal" couples have been devised that have proved of great value in technical operations.

A couple in considerable use has for the positive wire an alloy which analysis shows to consist of Cu 58.78, Ni 40.70, and slight impurities, while the negative wire is of iron with slight impurities.

For temperatures up to 1300° C., a certain pyrometer maker uses for the positive wire an alloy which analysis shows to consist of Ni 97.28, Si 2.15, Fe 0.35, Al 0.15: and for the negative wire an alloy consisting of Ni 88.67, Cr 10.75, Al 0.22, Si 0.15, Fe 0.10. For lower temperatures the same negative wire is employed in connection with a positive wire consisting of Ni 45.0, Cr 55.0.

Many base metal couples have a much higher thermoelectric power than the platinum-rhodioplatinum couple and so can be used in connection with more robust millivoltmeters. They have the disadvantages, however, of less uniform thermoelectric power, short life, and restricted temperature range.

17. The Construction of a Thermoelectric Couple. — The ends of the two wires constituting the hot junction should be fused together. The fusion may be readily accomplished by means of an oxyhydrogen flame, an oxyacetylene flame, or an electric arc. Before use a couple should be annealed. This may be accomplished by raising the entire length to redness by means of an electric current and then, depending upon the nature of the metals, either quenching in water or allowing it to slowly cool.

The two wires constituting the couple should be insulated throughout their length. For base metal couples, this may be accomplished by small quartz tubes or by a covering of purified asbestos string. For platinum couples it may be accomplished by means of beads or tubes of hard porcelain.*

For ordinary use the insulated wire constituting the "fire end" should be protected against chemical and mechanical injury by a sheath of iron, a chrome-nickel alloy, quartz, or Marquardt por-

* Asbestos must not be used on platinum couples.

celain. An iron sheath should not be used for temperatures above 800° C. Fused quartz will not break by sudden change of temperature and is available for temperatures up to 1200° C. Above this temperature, however, quartz gradually devitrifies and crumbles. Marquardt porcelain can be used up to 1600° C., if not heated or cooled so quickly as to crack.

Instead of two parallel wires, insulated from one another and enclosed in a protecting sheath, certain base metal couples consist of a rod of one metal placed axially within a tube of the other metal, with the rod and tube fused together at one end. Unless placed in some substance that will attack the material of the tube, such a cane-like "pyod" requires no protecting sheath.

18. Indicators for Thermoelectric Pyrometers. — The electromotive forces developed by a thermoelectric couple are measured either by a millivoltmeter or by a potentiometer. From a calibration curve constructed from a given cold-junction temperature, the scale of the millivoltmeter or potentiometer can be so divided that the instrument will indicate directly the temperature of the hot junction. A millivoltmeter or potentiometer with a scale divided so as to indicate temperatures directly is called a thermoelectric pyrometer indicator. The scale of a thermoelectric pyrometer indicator can be used only in connection with the thermo couple with which it was calibrated, or with one constructed of the same materials.

19. Millivoltmeter Indicators. — Thermoelectric pyrometer indicators are usually moving-coil millivoltmeters of considerable sensitiveness and fairly robust construction. In the most sensitive type, the coil is supported, above and below, by very thin metal wires. The most common method of support is by two jeweled bearings. Another successful method of support is by a single jeweled bearing at the center of the coil.

The electric resistance of a millivoltmeter should be so high compared to that of the remainder of the circuit, that the readings will not be appreciably altered by changes in the resistance of the circuit produced by temperature fluctuations. The resistance that the indicator must have in order that the potential

difference at its terminals may not vary more than a given amount when the resistance of the remainder of the circuit is altered can be readily found. Thus, letting E represent the resultant electromotive force of the couple, and r_1, r_2, r_3, the resistance of the couple, the connecting leads and the indicator, respectively, there will be a current I throughout the circuit given by the equation:
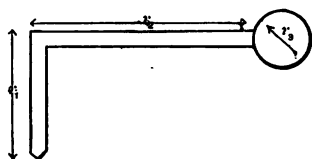
FIG. 16.

$$I = \frac{E}{r_1 + r_2 + r_3}.$$

The electromotive force of the couple develops a potential difference V, at the terminals of the indicator of a magnitude given by the equation:

$$I = \frac{V}{r_3}.$$

Equating the right-hand members of these equations

$$\frac{V}{r_3} = \frac{E}{r_1 + r_2 + r_3},$$

$$V = \frac{Er_3}{r_1 + r_2 + r_3}. \tag{5}$$

Problem. — Assuming that the temperatures of the hot and of the cold junction remain constant, and also that the resistance of the millivoltmeter remains constant, find the resistance that the millivoltmeter must have in order that the potential difference at its terminals may not change more than one per cent when the resistance of the remainder of the circuit changes from 2 ohms to 3 ohms.

Solution. — Since the temperature of each junction remains constant, the resultant electromotive force E will remain constant. Now when $r_1 + r_2 = 2$, we have (5),

$$V = \frac{Er_3}{2 + r_3}. \tag{6}$$

And since, when $r_1 + r_2 = 3$, the potential difference at the terminal of the indicator is to be 0.99 V, we may write (5),

$$0.99 \ V = \frac{Er_3}{3 + r_3}. \tag{7}$$

Solving for r_3 by dividing each member of (7) by the corresponding member of (6), we find the required resistance of the indicator to be

$$r_3 = 97 \text{ ohms.}$$

In millivoltmeters designed for use in connection with thermo-electric pyrometers, two general methods are in vogue for the prevention of changes in the indications being produced by fluctuations in the temperature of the indicator.

First, by the use of coils of zero temperature-resistance co-efficient. As all alloys of negligible or negative temperature coefficient have a high resistivity, it is customary to use a moving coil of about 10 ohms made of copper, in series with a multiplier, of not less than 100 ohms made of manganin or other alloy of zero or negative temperature coefficient.

Second, by properly altering the magnetic flux in the region occupied by the moving coil. If this flux be increased by the proper amount when the resistance of the coils of the indicator is increased, the indications will be unaffected by temperature changes. This result is accomplished automatically in the Thwing pyrometer millivoltmeters by a diminution of the air gap when the temperature rises.

20. The Potentiometer Method of Measuring Electromotive Forces. — Electromotive forces can be measured with greater precision by means of the potentiometer method than by means of a millivoltmeter. Though the measurement of an electro-motive force by means of a potentiometer involves an adjust-ment, whereas the millivoltmeter is direct reading, instruments are now available for use with thermoelectric couples, in which this adjustment is very easily made.

The rationale of the potentiometer method will be rendered clear by a consideration of the following diagrams:
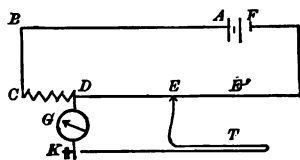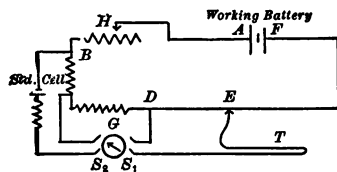
FIG. 17.   FIG. 18. .

Consider a circuit consisting of a conductor *ABCDF*, Fig. 17, joined to the terminals of a battery maintained at constant elec-

tromotive force. Suppose a line including the thermocouple T whose electromotive force is required, a galvanometer G, key K, and sliding contact E, to be connected into the circuit $ABCDF$, as shown. If the electromotive force of the thermoelectric couple is in the direction to oppose the potential difference at the points D and E due to the battery, a position of the sliding contact E can be found such that the potential difference between D and E due to the battery is equal and opposite to the potential difference between the same points due to the thermoelectric couple. The balance will be indicated by zero deflection of the galvanometer when the key K is closed. This potential difference can be determined by substituting for the thermoelectric couple a cell of known and constant electromotive force, and rebalancing by moving the sliding contact to some point E'. Thus if the current in the main circuit be I the resistance between D and E be R, that between D and E' be R', the potential difference between D and E be V, and that between D and E' be V', we have, when the thermoelectric couple is in place

$$I = \frac{V}{R},$$

and when the standard cell takes the place of the thermoelectric couple,

$$I = \frac{V'}{R'},$$

whence
$$\frac{V}{V'} = \frac{R}{R'}.$$

Since the thermoelectric couple produces no current when the potentiometer is in balance, its electromotive force E numerically equals the potential difference V. And, since the standard cell produces no current when the potentiometer is in balance, its electromotive force E' numerically equals the potential difference V'.

Thus,
$$\frac{V'}{V} = \frac{E}{E'} = \frac{R}{R'}.$$

If the slide wire be uniform, the resistance between any two

points will be proportional to the length between those points. Denoting the length DE by l, and the length DE' by l'

$$\frac{R}{R'} = \frac{l}{l'},$$

and the previous equation becomes

$$\frac{E}{E'} = \frac{l}{l'}.$$

Since for a particular wire and standard cell, $\dfrac{E'}{l'}$ is a constant quantity, which we may denote by c

$$E = cl. \tag{8}$$

Knowing the constant c, the whole slide wire can be marked off so as to indicate directly the electromotive forces corresponding to various points of the wire. So long as the battery between A and F has a constant electromotive force, any electromotive force E, within the range of the instrument, will be indicated by the position of the sliding contact when a balance is effected.

Though there are cells, which if used in series with a high resistance for but a few seconds at a time, maintain electromotive forces at a constant value through a period of several years, no actual battery maintains a constant electromotive force if supplying appreciable current for a long time. Consequently, the ideal arrangement diagrammed in Fig. 17 must be modified for practical use. Fig. 18 shows the addition of an adjustable resistance H to the main circuit, and a standard cell with a high resistance and a switch S_2 shunted about a portion of the main circuit. The purpose of the standard cell is to check the potential difference between B and C. In case this potential difference has not the required value, it can be regulated by varying the adjustable resistance H. In using this apparatus, the current in the main line is regulated till on closing the switch S_2 the galvanometer gives zero deflection. The apparatus can be calibrated by means of another standard cell as described in the preceding paragraph. Thereafter, before taking a set of readings, the current in the main line is first adjusted till on closing the

switch S_2 the galvanometer gives zero deflection; then with S_2
open, the sliding contact E is moved back and forth till on closing
the switch S_1, the galvanometer gives zero deflection. The
required electromotive force is then read from the scale beside
the calibrated slide wire.

21. Potentiometer Indicators for Thermoelectric Pyrometers.
— For a given length of slide-wire, greater sensitiveness is ob-

FIG. 19.

tained by throwing a shunt XY,
about the slide-wire, as shown in
Fig. 19.
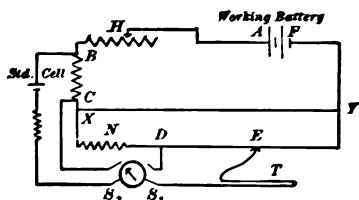
This arrangement is used fre-
quently in potentiometer indica-
tors for thermoelectric pyrometers.
The cold-junction error may be
compensated by the operator slid-
ing the galvanometer connection D, one way or the other by a
predetermined amount depending upon the departure of the tem-
perature of the cold end from the value when calibrated. The
top of a commercial potentiometer indicator arranged in this
manner is illustrated in Fig. 20. In this figure, H' is a knob
connected to the sliding contact of the variable resistance H,
Fig. 19, which regulates the current in the main circuit; E' is
a knob to adjust the position of the contact E on the slide wire;
D' is a knob to adjust the position of the galvanometer contact
D on the slide wire.

FIG. 20.

To use the cold-junction compensator D, one must have a temperature-electromotive force calibration curve of the particular thermocouple being used, for a certain fixed temperature t_0 of the cold junction. This curve indicates the electromotive force E_c that would be developed if the cold junction were at t_0 and the hot junction were at any temperature t_c. If in subsequent use, the cold junction be at t_c instead of at t_0, the temperature of the hot junction is that corresponding to the sum of E_c and that actually developed by the couple. Hence, by setting the cold-junction compensator at E_c, the balance position of the sliding contact E will give the electromotive force that would be produced if the cold junction were at t_0 and the hot junction were at its present temperature.

Potentiometer indicators are usually calibrated to read in millivolts. Such can be used in connection with any calibrated thermocouple. If, however, an indicator is to be used in connection with only thermocouples composed of the same two metals, it can be marked so as to indicate temperatures directly.

Instead of adjusting by hand the position of the sliding contact D, the cold-junction error can be automatically compensated by the use of a wire N, Fig. 19, of proper resistance made of a material whose temperature-resistance curve is of the same shape as the temperature-electromotive force curve of the thermocouple. In connection with thermocouples having a straight line calibration curve from $0°$ C. to about $50°$ C., nickel can be used for the coil N. As in the simple potentiometer, care must be taken to keep the potential difference between B and C constant. If the resistance of the nickel wire should change, the potential difference between B and C will change.

22. The Deflection Potentiometer. — When the electromotive force of a thermocouple is measured by means of a potentiometer of the ordinary type, a balance must be obtained for each reading made. This is a disadvantage when measuring temperatures which are varying. A dead beat voltmeter has the advantage of giving the electromotive force at any instant without any setting. The voltmeter, however, is not so accurate as the po-

tentiometer and the readings are affected by changes in the resistance of the thermocouple circuit.

A scheme of measurement which combines the two methods is made use of in the deflection potentiometer. The greater part of the electromotive force to be measured is balanced against a known potential difference as in the ordinary potentiometer and the remainder causes a deflection of the galvanometer which is calibrated to read potential differences. For a given required precision, if only a small part of the electromotive force be measured by means of the voltmeter then a larger percentage error in the voltmeter reading is allowable than if all of the electromotive force is read by the voltmeter.

By means of the deflection potentiometer the resistance setting need not be exact as the excess electromotive force can be read from the voltmeter. Thus sudden fluctuations of the electromotive force can be observed directly with a greater accuracy than is possible with a voltmeter.

Suppose Fig. 21 to represent a potentiometer circuit with a thermocouple connected for measurement.
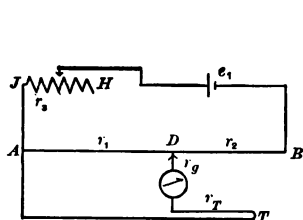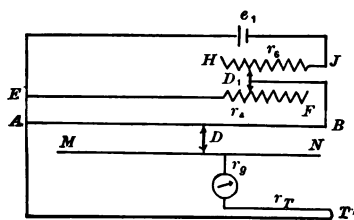
FIG. 21.   FIG. 22.

Let E be the electromotive force developed by the thermocouple and e_1, that of the working battery. Then if the balance is not complete there will be a current i_g, flowing through the galvanometer. From Ohm's law its value will be

$$i_g = \frac{\dfrac{e_1 \cdot r_1}{r_1 + r_2 + r_3} - E}{r_g + \dfrac{r_1 (r_2 + r_3)}{r_1 + r_2 + r_3} + r_T}.$$

If the denominator remains constant the current through the galvanometer is proportional to the difference of the potential difference across r_1 and the electromotive force to be measured. This means that r_g must be varied so as to keep the sum

$$r_g + \frac{r_1(r_2 + r_3)}{r_1 + r_2 + r_3} \text{ constant.}$$

The resultant resistance between A and D represented by the quantity

$$R_{AD} = \frac{r_1(r_2 + r_3)}{r_1 + r_2 + r_3}$$

will be minimum when the slider is at A or B, and will be maximum when the slider is at some intermediate position. Since r_g plus this quantity must be maintained constant, it follows that r_g must have its minimum value when this quantity is a maximum, and contrariwise.

This result may be accomplished by adding to the circuit in Fig. 21, two adjustable resistances MN and EF as illustrated in Fig. 22. In this figure, r_g may be considered to be made up of the resistance of the voltmeter and a portion of the resistance of MN. In adjusting the balance by moving the slider D from A to B, as much resistance must be added to the voltmeter by the wire MN as is taken out of the resultant resistance between A and D. For this adjustment, the resistance between E and B, including r_4, r_6, and the battery (corresponding to r_3 in Fig. 21), must be maintained constant.

The working current is maintained at the proper value by adjusting the position of the slider D_1. This adjustment of the position of D_1 is without effect on the resistance between E and B.

The adjustment of the working current through AB is obtained as in the ordinary potentiometer by balancing a standard cell across a portion of this resistance. Then the electromotive force to be measured is connected to the instrument and the slider D adjusted until the voltmeter pointer remains on the scale. The electromotive force then is obtained by adding to the potential difference across r_1 (which is indicated by the position of D), the

voltmeter scale reading.   The balance need never be complete and
the voltmeter reading will follow small fluctuations of the electro-
motive force without an adjustment of the slider D.

THE NORTHRUP PYROVOLTER. — In this method the electro-
motive force of the thermoelement is first balanced against the
potential difference at the terminals of a known resistance trav-
ersed by a current, and then this current is measured by a gal-
vanometer.   The product of the measured current and the con-
stant resistance equals the required potential difference.   The
circuit is represented in Fig. 23..   With the dial switch R in the
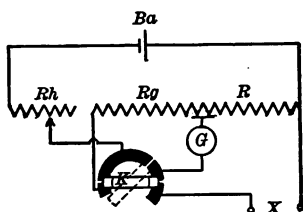
FIG. 23.

position indicated, the main current goes from Ba through the
rheostat Rh, the left-hand side of the switch, Rg, R and back to
the battery.   By joining to the binding posts X, in the proper
direction, the thermoelement whose electromotive force is re-
quired, the potential difference at the terminals of the thermo-
couple is opposed by that at the terminals of R.   The current in
R can be adjusted by means of the rheostat till these two poten-
tial differences are equal.   When balanced, the galvanometer
gives zero deflection.

If the dial switch be now rotated into the dotted position, the
current from the battery traverses Rh, the right-hand part of the
switch, the galvanometer, and R, back to the battery.   That is,
the current traverses the same circuit as before except that G
takes the place of Rg.   If the resistance of G equals that of Rg,
the current through R is the same as before.   That is, the current
through R when the two potential differences were balanced is

now indicated by the galvanometer. The product of the constant resistance R and the current producing any selected deflection can be marked beside the selected scale division, and thus the instrument divided so as to indicate potential difference directly.

The precision of the pyrovolter method is limited by that of the galvanometer. But the method is superior to the voltmeter method in that the electromotive force being measured is not altered by the introduction of the device; the indication is independent of the resistance of the lead wires; and the observed potential difference at the terminals of a source of electromotive force equals the electromotive force.

23. Recording Thermoelectric Pyrometers. — A recording thermoelectric pyrometer can be produced by substituting for the Wheatstone bridge and resistance coil of the recorder described in Art. 13, a potentiometer and thermoelectric couple such as is diagrammed in Fig. 19. In this case the slide wire DE, Fig. 19, would be bent into a circular arc, and the contact point E would be on the end of a radial arm operated by the shaft of the wheel A, Fig. 10. The potential difference between the points B and C, Fig. 19, can be maintained constant by an occasional adjustment, by hand, of the control rheostat H. The apparatus can also be arranged so that this adjustment will be done automatically.

There are also on the market several forms of recorders in which a millivoltmeter is used instead of a potentiometer. One successful form designed by the Wilson-Maeulen Co., is illustrated in Fig. 24. The record paper is drawn at a constant speed by means of clockwork under the pointer N of the millivoltmeter V. Every ten seconds the boom B chops down on the pointer. Directly under the boom, and separated from it only by the record paper and a typewriter ribbon, is a sharp straight edge. When the boom strikes the pointer a dot will be made on the paper where the pointer crosses the straight edge. The paper is so thin that the dot shows on both sides. In this manner a curve is automatically drawn coordinating time and millivoltmeter deflections.

This device can also be arranged to record the temperatures

of several different thermoelectric couples. For this purpose there is added a magnetically operated, clock controlled switch, which shifts the connection of the millivoltmeter every 80 seconds from one thermoelectric couple to the next. As the successive dots on the record merge into a line, the curve for each thermoelectric couple consists of a series of dashes, separated by spaces equal to the product of the length of a dash and the number of thermoelectric couples.
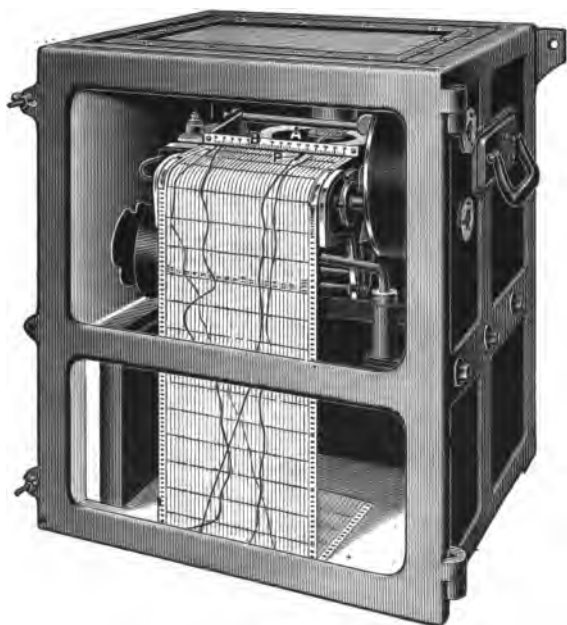
FIG. 24.

To readily distinguish between the different curves, a multiple color typewriter ribbon is employed — one color for each thermoelectric couple. The same switch that shifts the millivoltmeter connection from one thermoelectric couple to another, at the same time shifts the typewriter ribbon from one color to another.

24. The Cold-Junction Correction. — The resultant electromotive force developed by a given thermoelectric couple depends

upon the difference of temperature of the hot and cold junctions, and also upon the actual temperatures of the hot and cold junctions. In calibrating a couple, the cold junction is maintained at some definite temperature (usually $0°$ C. or $20°$ C.), the hot junction is raised to known temperatures, and the electromotive forces thereby produced are noted. A calibration curve coordinating temperatures of the hot junction and the corresponding electromotive forces produced when the cold junction is at the assigned temperature can be drawn. ·

After a certain thermoelectric couple has been calibrated, the scale of the millivoltmeter used with it may be divided so as to indicate temperatures instead of millivolts. Such a direct reading instrument will give correct indications only, (a) when used with the thermoelectric couple with which it was calibrated or one with the same thermoelectric properties; (b) when the cold junction of the thermoelectric couple is at the temperature maintained during calibration.
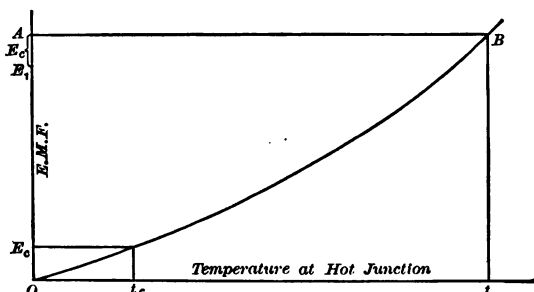
FIG. 25.

In industrial practice it is often more convenient to maintain the temperature of the cold junction at a constant temperature different than the one it had when the couple was calibrated. In this event the indicator reading must be modified by a "cold-junction correction." In this article, the temperature of the cold junction is constant, but is not the same as when the instrument was calibrated. Two cases will be considered.

FIRST. — *Indicator reading in Millivolts.* — In Fig. 25 is shown

a curve representing the relation between the temperature of the hot junction and the electromotive force of a couple having the cold junction maintained at 0° C. It will be noted that as zero electromotive force corresponds to zero temperature difference, this curve passes through the origin of temperatures and electromotive forces.

In the case of a thermoelectric couple calibrated at 0° C., when used with the cold junction at $t_c°$, the temperature of the hot junction is not the temperature corresponding to the electromotive force indicated by the millivoltmeter, but is the temperature corresponding to an electromotive force equal to the sum of the electromotive force indicated by the millivoltmeter (E_1, Fig. 25) and the electromotive force (E_c, Fig. 25), that would be developed if the cold junction were at 0° and the hot junction at $t_c°$.

For example, let it be required to determine the temperature of the hot junction corresponding to an indicated electromotive force E_1, Fig. 25, when the cold junction is at temperature t_c. Add to OE_1, the distance $E_1A = OE_c$. From A, draw a line AB parallel to the temperature axis till it intersects the calibration curve for a cold junction at 0°. Project the latter point of intersection B on to the temperature axis. The point t gives the required temperature of the hot junction.

It will be seen from this construction that if the calibration curve be a straight line, the cold junction correction for a cold-junction temperature t_c is ($t_c - t_0$), where t_0 is the temperature of the cold junction when the couple was calibrated. In this case, the cold junction correction is the same for all electromotive forces.

The calibration curve of most couples, however, is not a straight line. When the calibration curve is not a straight line, the cold junction correction does not equal ($t_c - t_0$), and it is not of the same magnitude for all electromotive forces.

The calibration curves of many base metal couples are sufficiently near being straight lines, that, for departures from the standard cold junction temperatures of as much as 10° C., the error intro-

duced by assuming the cold junction correction to be $(t_c - t_0)$ is not greater than the error allowable in industrial practice.

SECOND. — *Indicator reading in Degrees.* — In Fig. 26, let the curve represent the calibration curve of the thermoelectric pyrometer when the cold junction is at $0°$ C. Thus, when the cold junction is at $0°$ C., and the hot junction is at $t°$ C., there will be developed an electromotive force E. When the cold junction is at $0°$ C., and the hot junction is at $t_c°$, there will be developed an electromotive force E_c. When the cold junction is at $t_c°$, and the hot junction is at $t°$ C., there will be developed an electromotive force E_1, such that

$$E_1 = E - E_c. \tag{9}$$

The millivoltmeter will now not indicate $t°$, but will indicate some lower temperature $t_1°$. The difference between the temperature of the hot junction and the value indicated on the millivoltmeter is the cold junction correction. That is, the cold junction correction,

$$p = t - t_1.$$

The magnitude of the cold junction correction p is now to be determined according to a method due to Paul D. Foote (Bull. Bureau of Standards, Vol. 9, pp. 553–565). We will first express

FIG. 26.

the values of t and t_1 in terms of the corresponding electromotive forces E and E_1. The thermoelectromotive force developed when the junctions are at different temperatures is a function of the temperature difference. When the cold junction is at $0°$ C., and the hot junction is at $t°$ C., there will be developed an electromotive force having the value

$$E = f(t), \tag{10}$$

where the function f, depends upon the nature of the two metals. This equation gives the relation between the electromotive force impressed on the millivoltmeter and the meter readings.
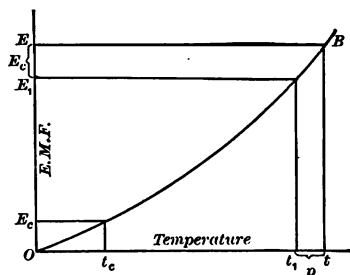
When the cold junction is at $t_c°$ C., and the hot junction at $t°$ C., then there will be developed an electromotive force E_1. Since the apparatus is assumed to be calibrated with the cold junction at $0°$ C., the millivoltmeter will now not indicate $t°$, but will indicate a lower temperature t_1. In this case, since E_1 is the electromotive force impressed on the millivoltmeter, and t_1 is the meter reading,

$$E_1 = f(t_1). \qquad (11)$$

Since (10) $E = f(t)$, and (9) $E = E_1 + E_c$,

$$f(t) = E_1 + E_c.$$

Expressing temperature explicitly in terms of E_1 and E_c, we have

$$t = \phi\,(E_1 + E_c),$$

where ϕ is the inverse function of f.
Also, from (11),

$$t_1 = \phi\,(E_1). \qquad (12)$$

Consequently, the magnitude of the cold-junction correction

$$p\,[= t - t_1] = \phi\,(E_1 + E_c) - \phi\,(E_1). \qquad (13)$$

Expanding $\phi\,(E_1 + E_c)$ by Taylor's theorem,

$$\phi\,(E_1+E_c) = \phi\,(E_1) + \frac{E_c\,d\phi\,(E_1)}{1\quad dE_1} + \frac{E_c{}^2}{2!}\frac{d^2\phi\,(E_1)}{dE_1{}^2} \;\cdots\; + \frac{E_c{}^n}{n!}\frac{d^n\phi\,(E_1)}{dE_1{}^n}.$$

Whence (12),

$$p = \phi\,(E_1) + \frac{E_c}{1}\frac{d\phi\,(E_1)}{dE_1} + \frac{E_c{}^2}{2!}\frac{d^2\phi\,(E_1)}{dE_1{}^2} \;\cdots\; + \frac{E_c{}^n}{n!}\frac{d^n\phi\,(E_1)}{dE_1{}^n} - \phi(E_1)$$

$$(14)$$

Under certain experimental conditions this expression can be reduced to a much simpler form. Thus if E_c be small in comparison with E_1, all terms involving the second and higher powers of E_c may be neglected without sensibly affecting the magnitude of p. Noting that the first and last terms of the right-hand member cancel, the introduction of this approximation gives us

$$p \doteqdot E_c\frac{d\phi\,(E_1)}{dE_1}. \qquad (15)$$

Differentiating (12) with respect to dE_1,

$$\frac{dt_1}{dE_1} = \frac{d\phi\ (E_1)}{dE_1},$$

whence (15) becomes

$$p \doteqdot E_c \frac{dt_1}{dE_1} \doteqdot \frac{E_c}{\left(\dfrac{dE_1}{dt_1}\right)}, \tag{16}$$

or, in words, when the couple is calibrated with the cold junction at $0°$ C., and the couple is afterward used with the cold junction at $t_c°$ C., the observed temperature indication must be increased by the quotient obtained by dividing the electromotive force generated when the junctions are at $0°$ C., and $t_c°$ C., respectively, by the slope of the calibration curve at the apparent temperature of the hot junction.

The case is similar in which the thermoelectric couple was calibrated with the cold junction not at $0°$ C., but at $t_c{}'$, and the couple is subsequently used with the cold junction at $t_c{}''$. Thus, representing by $E_c{}'$ the electromotive force generated when the junctions are at $t_c{}'$ and $t_c{}''$, respectively, and by $E_c{}''$, the electromotive force generated when the junctions are at $t_c{}''$ and the apparent temperature t_1, respectively, and following the preceding method, we obtain for the present case,

$$p \doteqdot E_c{}' \frac{dt_1}{dE_c{}''} \doteqdot \frac{E_c{}'}{\dfrac{dE_c{}''}{dt_1}}. \tag{17}$$

Or, in words, when the couple is calibrated with the cold junction at $t_c{}'$, and the couple is afterward used with the cold junction at $t_c{}''$, the observed temperature indication must be increased by the quotient obtained by dividing the electromotive force when the junctions are at $t_c{}'$ and $t_c{}''$, respectively, by the slope of the calibration curve at the observed apparent temperature.

Problem. — In calibrating a certain thermoelectric pyrometer with the cold junction maintained at 0° C., the following data were obtained:

Indicator deflection, °C.	Electromotive force, microvolts.
100	1,600
300	5,400
600	12,600
900	21,600
1100	28,600
1300	36,400
1400	40,600

Construct curves coordinating indicator deflections and corrections to be added when the cold junction is at 20° C., 50° C., 70° C., and 100° C.

Solution. — The calibration curve for the cold junction at 0° C., obtained by plotting the above deflections and electromotive forces is as shown in Fig. 27.
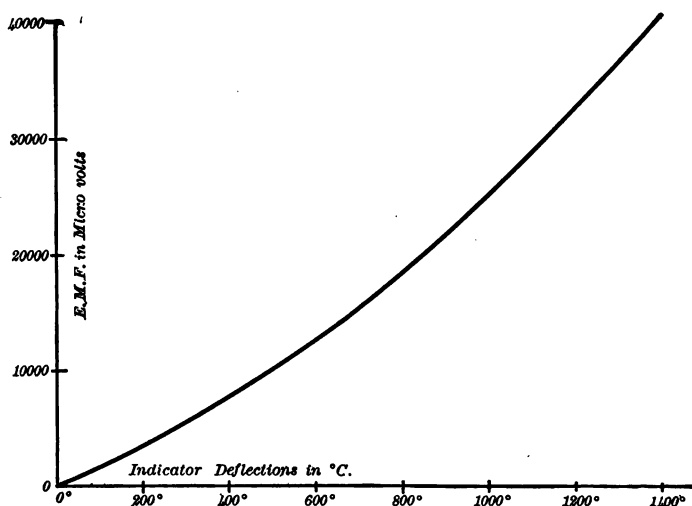
FIG. 27.

An inspection of this curve would suggest to a person familiar with the appearances of curves and the forms of their equations, that this curve might be represented by an equation of the form:

$$E = bt + ct^2 \qquad (18)$$

To find the values of the constants b and c we may select any two points of the curve, for example (300° C., 5400 microvolts) and (1100° C., 28600 microvolts). We then may write:

$$5400 = 300\,b + (300)^2\,c. \tag{19}$$
and
$$28{,}600 = 1100\,b + (1100)^2\,c. \tag{20}$$

To eliminate (b), multiply each term of (19) by 33, and each term of (20) by 9. Then,

$$178{,}200 = 9900\,b + 2{,}970{,}000\,c. \tag{21}$$
$$257{,}400 = 9900\,b + 10{,}890{,}000\,c. \tag{22}$$

Subtracting each member of (21) from the corresponding member of (22),

$$79{,}200 = 7{,}920{,}000\,c,$$

whence,

$$c = 0.01.$$

Substituting this value of c in (19),

$$5400 = 300\,b + 900,$$

whence

$$b = 15.$$

On substituting these values of b and c in the general equation (18), the definite equation of the curve is found to be

$$E = 15\,t + 0.01\,t^2. \tag{23}$$

By means of this equation the quantities in the right-hand member of (16) can be found. Thus suppose it be required to find the cold-junction correction for an indicated temperature at 1000° C., when the cold junction is at 30° C. From (23)

$$E_c = 15\,(30) + 0.01\,(30)^2 = 459\ \text{microvolts}. \tag{24}$$

Again, differentiating E in (23) with respect to t, we obtain

$$\frac{dE}{dt} = 15 + 0.02\,t.$$

For an indicated temperature $t_1 = 1000°$ C. we would have

$$\left(\frac{dE_1}{dt_1}\right)_{1000°} = 15 + 0.02\,(1000) = 35.$$

Consequently, when the cold junction is at 30° the correction to be added to an indicated temperature of 1000° C., is (16)

$$p = \left[\frac{E_c}{\left(\dfrac{dE_1}{dt_1}\right)_{1000°}}\right] = \frac{459}{35} = 13°.1\ \text{C.} \tag{25}$$

In the same manner the following tables were computed:

t_c	E_c	t_c	E_c
° C.	Microvolts.	° C.	Microvolts.
10	151	60	936
20	304	70	1099
30	459	80	1264
40	616	90	1431
50	775	100	1600

t_1	$\left(\dfrac{dE_1}{dt_1}\right)_{t_1}$	t_1	$\left(\dfrac{dE_1}{dt_1}\right)_{t_1}$
° C.		° C.	
100	17	800	31
200	19	900	33
300	21	1000	35
400	23	1100	37
500	25	1200	39
600	27	1300	41
700	29	1400	43

By substituting these values in (16),

$$p \doteqdot \frac{E_c}{\left(\dfrac{dE_1}{dt_1}\right)},$$

the values in the following table were computed. From the data in this table the correction curves for cold junctions at 20° C., 50° C., 70° C., and 100° C., have been plotted in Fig. 28.
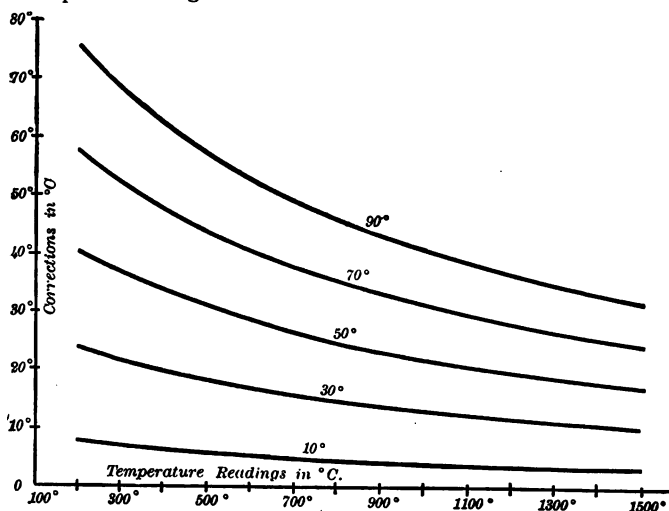
FIG. 28.

Values of the cold-junction correction to be added to the temperature readings of a thermoelectric couple which when the cold junction is at 0° C. has a calibration curve of the form $E = 15\,t + 0.01\,t^2$.

t_1	Cold-junction temperatures.									
	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°
200	7.9	16.0	24.2	32.4	40.8	49.3	57.9	66.5	75.4	84.2
300	7.2	14.5	21.8	29.3	36.9	44.6	52.4	60.2	68.2	76.3
400	6.6	13.2	19.9	26.7	33.7	40.7	47.8	55.0	62.4	59.5
500	6.0	12.1	18.4	24.6	31.0	37.4	44.0	50.7	57.4	64.0
600	5.6	11.2	17.0	22.5	28.7	34.8	40.8	46.9	53.1	59.3
700	5.2	10.5	15.8	21.2	26.8	32.3	37.9	43.7	49.4	55.2
800	4.9	9.8	14.8	19.9	25.0	30.2	35.4	40.8	46.2	51.7
900	4.6	9.2	13.9	18.7	23.5	28.4	33.3	38.4	43.4	48.5
1000	4.3	8.7	13.1	17.7	22.2	26.8	31.4	36.2	40.9	45.7
1100	4.1	8.2	12.4	16.7	21.0	25.3	29.7	34.2	38.7	43.2
1200	3.9	7.8	11.8	15.8	19.9	24.0	28.2	32.4	36.7	41.0
1300	3.7	7.4	11.2	15.0	18.9	22.8	26.8	30.9	35.0	39.0
1400	3.5	7.1	10.7	14.3	18.0	21.8	25.6	29.4	33.3	37.2
1500	3.4	6.8	10.2	13.7	17.2	20.8	24.5	28.1	31.8	35.6

25. Cold-junction Correction when the Temperature of the Cold Junction is not Constant. — If the temperature of the cold junction of a thermocouple does not remain constant but yet can be observed at the same time that the indicator reading is taken, then the corrections that must be applied to the indicator reading can also be obtained. For, from the expression for the correction (16),

$$p \doteqdot \frac{E_c}{\left(\dfrac{dE_1}{dt_1}\right)},$$

the correction to be applied to the reading will be proportional to the electromotive force developed when one junction is at 0° C., and the other is at the actual temperature of the cold junction. Thus, if at one time the cold-junction temperature is t_c, and at another time is t_c', then the correction in the second case is in terms of that in the first case,

$$p' \doteqdot p_1 \frac{E_c'}{E_c}.$$

However, since the ratio $\left(\dfrac{E_c'}{E_c}\right)$ is very nearly equal to the ratio of the temperatures of the cold junction, we may write

$$p' \doteqdot p_1\left(\frac{t_c'}{t_c}\right). \tag{26}$$

Then if we know the corrections to be applied to the observed readings when the cold junction is at any temperature, we can obtain by a simple proportion the correction when the cold-junction temperature is at any other known value.

The degree of accuracy of this method may be checked from the table at the end of the previous article. For example, check the fifth part of the corrections in the 50° column with the values in the 10° column. The errors are less than 1° C.

. A convenient method would be to plot corrections against indicated readings, as in Fig. 28, for the maximum cold-junction temperature that would be attained, and then interpolate. For example, suppose that the curve for 50° C. were plotted. If the indicated reading was 500° C., and the cold-junction temperature was 30° then the correction to be applied would be (26),

$$p' \doteqdot p_1\frac{30}{50}.$$

Fig. 28 shows that for the pyrometer there considered, when $t_c = 50°$, and $t_1 = 500°$, $p_1 = 31°$.
Whence, when $t = 30°$, the cold-junction correction is

$$p \doteqdot 31\frac{30}{50} \doteqdot 18°.6.$$

Problem. — The thermocouple, the equation of which is $E = 15\,t + 0.01\,t^2$ when the temperature of the cold junction is 0° C., was used to indicate a series of temperatures when the cold junction was not maintained at a constant temperature. The temperatures of the cold junction at various indicated temperatures of the hot junction were as given below. It is required to determine the actual temperature of the hot junction corresponding to the various observed indicated temperatures.

Hot junction (indicated).	Cold junction.	Hot junction (indicated).	Cold junction.
° C.	° C.	° C.	° C.
200	20	900	29
300	22	1000	24
400	25	1100	27
500	28	1200	30
600	31	1300	25
700	36	1400	30
800	32	1500	35

Solution. — Arrange these data in two columns as in the following table. In the third column put the corrections to be applied if the cold junction had been maintained at some constant temperature other than 0°. For this particular thermocouple such corrections for various cold-junction constant temperatures are given in the table at the end of Art. 24. For the use of this solution the values for any particular constant temperature may be selected. The third column of the table below gives the values for 50° C., expressed in the nearest integer. The values in the second and third columns substituted in (26) give the actual corrections to be added to the indicated temperatures under the conditions specified in the present problem. These corrections are given in the fourth column.

Hot junction (indicated), t_1	Cold junction, t_o'	Correction if cold junction were at 50° C., p_1	Actual correction, $p' \doteq p_1 \left(\dfrac{t_o'}{t_o} \right)$	Hot junction (actual), t
° C.	° C.	° C.	° C.	° C.
200	20	41	41 (20 ÷ 50) = 16	216
300	22	37	37 (22 ÷ 50) = 16	316
400	25	34	34 (25 ÷ 50) = 17	417
500	28	31	31 (28 ÷ 50) = 17	517
600	31	29	29 (31 ÷ 50) = 18	618
700	36	27	27 (36 ÷ 50) = 19	719
800	32	25	25 (32 ÷ 50) = 16	816
900	29	23	23 (29 ÷ 50) = 13	913
1000	24	22	22 (24 ÷ 50) = 11	1011
1100	27	21	21 (27 ÷ 50) = 11	1111
1200	30	20	20 (30 ÷ 50) = 12	1212
1300	25	19	19 (25 ÷ 50) = 10	1310
1400	30	18	18 (30 ÷ 50) = 11	1411
1500	35	17	17 (35 ÷ 50) = 12	1512

26. Shop Methods for Reducing the Errors due to Variation in the Temperature of the Cold Junction. — If the temperature of the cold junction is higher than it was when the pyrometer was calibrated, the indicated temperature will be too low; and if the

temperature is lower than it was when the instrument was calibrated, the indicated temperature will be too high. The obvious method to prevent these errors is to maintain the cold junction at a constant temperature.

The temperature of the cold junction can be maintained at an approximately constant temperature by enclosing it in a box with one or more incandescent lamps that are automatically turned on or off by a thermostat as the temperature of the box falls below or rises above a certain selected value.

The temperature of the cold junction can also be maintained at an approximately constant temperature for a considerable period either by enclosing it in a jacket through which flows a steady stream of water from the city mains, or by burying it at a depth of six to ten feet in the ground. The latter method requires that the wires composing the thermocouple shall be of considerable length, or that extension leads be used composed of either the same materials as the wires of the couple to which they are joined, or of other materials of the same thermoelectric properties. In the case of base metal couples there is no difficulty in providing extension leads of the same materials as the metals composing the couple; but in the case of the platinum couples the expense would usually be prohibitive. To overcome this difficulty various alloys are on the market which, through the range of temperatures to which the cold junction would be apt to be subjected, have the same thermoelectric properties as the standard platinum-platinum alloy couples. The use of these various alloys for extending the wires of a couple is guarded by patents.

For the degree of precision required in commercial practice the following methods are in successful use for overcoming the errors due to fluctuations in the temperature of the cold junction of a thermoelectric pyrometer.

(a) *The Use of a Compensator Couple.* — The cold junction can, in effect, be removed to a place where it is possible to maintain the temperature constant by the use of a supplementary thermoelectric couple.

In Fig. 29, *T* represents a thermoelectric couple employed to

measure the difference between the temperature of the hot region x, and the cold region y, maintained at a constant temperature. T_s is a supplementary couple of the same thermoelectric properties as T. The two couples are joined in opposition. In practice T would be an expensive rhodioplatinum couple, and T_s would be one composed of cheaper materials. The ends a, b, c are so close together that they will all be at a common temperature. G is a millivoltmeter or other indicating instrument.
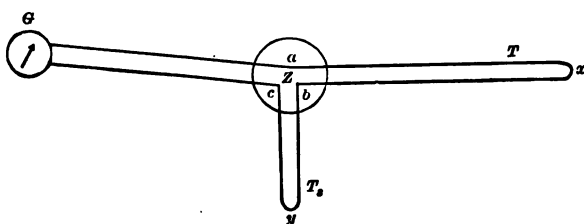
Fig. 29.

Denote the temperatures of x, y, and the common temperature of a, b, c, by the symbols t_x, t_y, and t_z, respectively. Then when $t_x > t_z > t_y$, current flows along the path $axbyc$. If now t_z diminishes while t_x and t_y remain unchanged (usually not equal), the electromotive force in T_s will diminish to the same extent as that in T increases, thereby leaving the resultant current in the circuit unchanged.

If, however, t_z increases while t_x and t_y remain constant, the electromotive force in T will diminish and the electromotive force in T_s will increase to the same extent, again leaving the resultant current unchanged.

When $t_x > t_y > t_z$ current flows along the paths axb and cyb. If now t_z diminishes while t_x and t_y remain constant, the electromotive force in T will increase, and the opposing electromotive force in T_s will increase in the same degree, thereby leaving the resultant current in the circuit unchanged. If, however, t_z increases while t_x and t_y remain unchanged, the electromotive force in T will diminish and the opposing electromotive force in T_s will

diminish to the same extent, thereby leaving the resultant current in the circuit unchanged.

It is thus seen that any change in the temperature of z is without effect on the indicated reading.

(b) *Adjustment of the Zero Point of the Millivoltmeter.* — When the thermoelectric properties of the couple are such that throughout the entire scale of the indicating instrument equal spaces correspond to equal changes of the temperature of the hot end of the couple, the correct temperature of the hot junction is obtained by adding to the indicated temperature the number of degrees that the cold junction is hotter than it was when the instrument was calibrated. This addition or subtraction is often done by shifting the zero point of the scale of the indicator relative to the pointer through the space corresponding to the difference between the present temperature of the cold junction and the temperature when the instrument was calibrated. After this adjustment has been made, the temperatures indicated on the millivoltmeter will be correct.

When this method is employed an ordinary mercury-in-glass thermometer is usually kept at the cold junction and the zero point of the millivoltmeter readjusted by hand whenever a change in temperature of the cold junction occurs. Devices are on the market for automatically changing the zero point of the millivoltmeter when the temperature of the cold junction changes.

This method is available only when the calibration curve coordinating potential differences and millivoltmeter deflections is a straight line.

(c) *Compensating Wheatstone Bridge.* — In Art. 10, the Wheatstone bridge is explained and the equation stated. Suppose the thermoelectric pyrometer GT is put in place of the galvanometer of a Wheatstone bridge. When (4)

$$\frac{r_1}{r_2} = \frac{r_3}{r_4},$$

no current from the battery will flow through the millivoltmeter, and the millivoltmeter indication will be due entirely to the

difference in temperature of the junctions of the thermoelectric couple. If the resistance of one of the bridge arms is changed, then a current from the battery will traverse the millivoltmeter.

Suppose the arm *BC* consists of wire of a high resistance-temperature coefficient and the three other arms consist of wires of zero resistance-temperature coefficient. Then with the battery connected as shown in the diagram, when the temperature of the Wheatstone bridge increases, current from the battery will traverse the millivoltmeter in the direction *BGD*. The increase in temperature of the cold junction of the thermoelectric couple will at the same time reduce the current flowing through the millivoltmeter due to the couple.

It is thus seen that by properly selecting the materials for the bridge arms, an arrangement can be produced that will give millivoltmeter readings that are independent of the temperature of the cold junction. In practice,

FIG. 30.

the four bridge arms, the battery and the millivoltmeter are enclosed in one case, and the ends of the thermoelectric couple joined to terminals on the case. After being once adjusted, there will be no cold-junction error so long as the electromotive force of the battery remains constant.
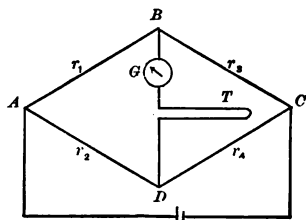
27. Advantages and Disadvantages of the Thermoelectric Method of Measuring Temperatures. — This method is available for measuring temperatures from the boiling point of liquid air ($-184°$ C.) up to $1500°$ C. The method is superior to other high temperature methods in the following respects:

(*a*) Ease of observation;

(*b*) Adaptability to a variety of purposes;

(*c*) Cheapness of apparatus;

(*d*) Robustness of apparatus and ease of repair;

(*e*) Availability for automatically making a permanent record of temperature extending over a considerable interval of time.

The points in which the method is inferior to some other methods are:

(1) The trouble involved in making the cold-junction correction. This is more serious when the range of temperature is small.

(2) On account of the small electromotive forces produced, very sensitive millivoltmeters are required. For example, with the cold junction at 0° C., the electromotive force of the rhodioplatinum couple is 18 millivolts at 1600° C., and that of the various nickel couples is about 60 millivolts at their highest ranges.

(3) Rhodioplatinum couples give diminished electromotive forces if allowed to remain long above 1200° C., or if employed in an atmosphere of contaminating gases.

(4) The high cost of platinum makes it necessary to use small wires. Such a thermoelectric element will have appreciably different resistances when immersed to varying depths in a furnace. On account of this fact, the millivoltmeter reading will depend upon the length of the couple immersed in the hot source.

28. The Installation of Thermoelectric Pyrometers. — On account of the robustness and compactness of the apparatus, the low cost of installation, and maintenance, ease of operation, wide temperature range, and degree of precision, the thermoelectric pyrometer is probably more generally employed than all other classes of pyrometers together. Couples made of the platinum group of metals can be used for short periods up to 1500° C., with a precision to within 1° C. There are base metal couples that can be used up to 1200° C. with a degree of precision within most industrial requirements. All base metal couples, however, used in measurements that are required to be trustworthy within 5° C. should be frequently checked against a rhodioplatinum standard.

All couples must be protected from oxidizing and reducing gases or anything else that would contaminate the metals composing them. For this purpose are employed protecting tubes or sheaths of pure iron, pure nickel, Marquardt mass, fused quartz, chamotte, carborundum, clay, graphite, corundite, and special alloys for particular corrosive materials. Marquardt mass tubes can be used continuously at temperatures as high as 1300° C., so long as

they are not subjected to sudden changes of temperature. If their temperature be suddenly changed, they will crack. They are quite unsuited to use where they would be subjected to shooting flames. Fused quartz can be used continuously up to 1100° C. Above 1200° C., quartz devitrifies and crumbles, and, in the presence of volatile reducing agents such as carbon or hydrogen, forms volatile silicides which will destroy platinum. Fused quartz will not crack when subjected to a change of temperature, however sudden.

Marquardt mass and fused quartz tubes designed for rough handling should be protected with a sheath of some material of greater mechanical strength. Chamotte sheaths can be used in temperatures up to 1500° C. They are not broken by sudden changes in temperature. They cannot be used in molten baths, nor in reducing or alkaline gases. Carborundum sheaths can be used at very high temperatures, under both oxidizing and reducing conditions. Chlorine, however, begins to act upon carborundum at about 950° C. Basic slags also attack it. Clay, graphite, and corundite sheaths have a wide application in brick and pottery kilns, glass melting furnaces and large annealing ovens.

To avoid any bending of the protecting sheath when subjected to high temperatures, the couple should either be suspended vertically or supported at two or more points.

When a thermoelectric pyrometer is calibrated there is a certain resistance in circuit. If a millivoltmeter indicator is employed, the same resistance as that in circuit when the instrument was calibrated must be maintained in all subsequent use. With a potentiometer indicator, the resistance in circuit need not be constant.

Due regard must be had to the reduction of the cold-junction error. For most industrial operations in which base metal couples are employed it is sufficient to use leads of the same materials as the couples, and either bury the cold junction six or eight feet under ground, or surround the cold junction with a jacket through which flows water from the mains.

Exp. 2. Calibration of a Thermoelectric Couple

THEORY OF THE EXPERIMENT. — Read Arts. (14–19). A thermoelectric pyrometer consists of a thermoelectric couple in connection with an arrangement for indicating the electromotive force between the hot and the cold junctions. For commercial purposes a millivoltmeter of suitable sensitiveness and resistance is a satisfactory indicator, but for some precise work a potentiometer is required.

In the case of couples found useful in actual measurements, the relation between temperature difference and electromotive force through a considerable temperature range can be expressed by a simple equation. For couples of different components, different equations are required. For most couples used in commercial work, one or the other of the following equations holds with a fair degree of approximation throughout a considerable temperature range.

$$E = a + bt + ct^2, \tag{27}$$
$$\log E = A \log t + B, \tag{28}$$

where E is the electromotive force expressed in millivolts for a temperature difference of $t°$ C., between the hot and cold junction, while a, b, c, A, and B are constant quantities for the given couple.

The purposes of this experiment are: first, to construct from experimentally determined data a curve coordinating the temperature difference and the electromotive force of a given thermoelectric element; and secondly, to determine the departure of this empirical curve from the curves expressed by (27) and (28).

If through the range of actual measurement the empirical curve can be represented by a known equation, then it is highly probable that the curve extended, or "extrapolated," somewhat beyond the range of these measurements by means of its equation, will also represent the relation between the two variables in the regions beyond the actual measurements. For example, if a certain equation represents the relation between temperature difference and electromotive force of a given thermoelectric couple from 400° to 800° C., it is highly probable that the same equation will

represent the relation between these quantities from 300° to 900° C. This furnishes a convenient device for extending a curve somewhat beyond the range convenient for experimental observations.

For this experiment several definitely known and easily produced temperatures are required. These conditions are most satisfactorily met by the melting points of metallic elements and salts. The following melting points are convenient for the calibration of the thermoelectric pyrometers:

Substances.	Melting points, ° C.
Tin....................	232
Bismuth..............	270
Lead.................	327
Zinc..................	419
Antimony.............	630
NaCl.................	800
BaCl$_2$.................	950
Silver................	961
Copper...............	1083
Nickel...............	1452

The temperature at which a substance melts is that at which the solid and liquid states remain together in thermal equilibrium. The point at which this condition obtains can be inferred as follows:

With one junction of the uncalibrated thermoelectric couple in a bath maintained at constant temperature, and the other junction in a mass of the melted substance, observe the electromotive force as the substance slowly cools. It will be found that as the substance cools the electromotive force decreases; that after cooling a certain amount the electromotive force remains constant for an appreciable interval of time; that during this interval the substance is changing from the liquid to the solid state; and that when all the substance has solidified, the electromotive force resumes its fall. The temperature of the substance during the time-interval of constant electromotive force, that is, of constant temperature, is the freezing point of the substance. The value of the freezing point is obtained from tables. Knowing the freezing points of a number of substances, together with the corre-

sponding electromotive force of a given thermoelectric couple, a calibration curve for the given couple can be constructed co-ordinating temperature differences and potential differences.

To locate the freezing (or melting) point of a substance, the substance is melted; the supply of heat is turned off; and while the substance is cooling, observations of the electromotive force of the thermoelectric couple being tested are taken every half minute. Make a cooling curve by plotting microvolts as ordinates and seconds as abscissas. This curve should extend from a temperature somewhat above the freezing point to a temperature somewhat below the freezing point.
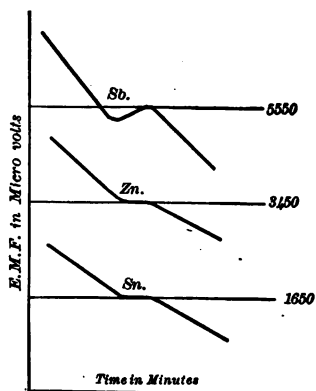
FIG. 31.

Typical cooling curves are shown in Fig. 31. From these curves it will be observed that antimony undercools and then rises to the freezing point. With the particular thermoelectric couple used, the electromotive force corresponding to the freezing point of tin is 1650 microvolts, that corresponding to the freezing point of zinc is 3450 microvolts and that corresponding to the freezing point of antimony is 5550 microvolts. The temperatures of the freezing substances are given in the table above.

MANIPULATION. — In the manner indicated, find the electromotive force corresponding to the freezing point of five substances, and construct a curve in which these are plotted as ordinates and the corresponding freezing points are plotted as abscissas. This is the experimentally determined calibration curve of the given thermoelectric pyrometer.

In case the indicator of the pyrometer is divided so as to read temperatures instead of microvolts, the ordinates of the calibration curve would represent pyrometer readings instead of micro-volts. If an indicator arranged to give temperatures is correctly divided, and if the same scale is used to plot pyrometer readings

and freezing points, then the calibration curve will be a straight line equally inclined to the two axes.

In the calibration of a thermoelectric pyrometer, the couple should be protected from hot gases or molten substances that would alter the materials of which it is composed. The couple should be immersed in the molten metals to about the same depth it is to be immersed in future use. For most commercial purposes an immersion of 20 cm. will be sufficient. The calibrating baths of easily oxidizable metals should be covered by a layer of about 2 cm. of powdered carbon.

If the empirical calibration curve can be expressed by an equation having the form of (27) or (28) then it can be extrapolated to lower and also to higher values than were obtained in the experiment. The closeness with which these equations represent the curve is now to be determined.

For example, assume for the moment that an equation of the form (27) represents the empirical calibration curve. The validity of this assumption will now be tested. Since the equation contains three independent variables, three equations will be required for the determination of their values. These three equations can be set up from the coordinates of any three points of the curve. Thus, representing numerical values of the coordinates of any three selected points by the symbols (E_1, t_1), (E_2, t_2), and (E_3, t_3), we can write:

$$E_1 = a + bt_1 + ct_1^2,$$
$$E_2 = a + bt_2 + ct_2^2,$$
$$E_3 = a + bt_3 + ct_3^2.$$

Since the empirical curve gives the actual values of all the quantities in these equations with the exception of the three constants, a, b, c, the values of these constants can be computed by the ordinary method for solving simultaneous equations. If the empirical curve can be represented by an equation of the form

$$E = a + bt + ct^2$$

then the definite equation of the curve traversing the three selected

points will be obtained by substituting for the constants a, b, and c, the numerical values just computed.

Substitute in this definite equation various arbitrary values of t, within the range of the empirical curve, and compute the corresponding values of E. Plot these computed points on the sheet with the empirical curve. If this "computed curve" coincides with the empirical curve, then the definite equation above obtained represents the empirical curve throughout the range of the experiment. If this be true, the empirical curve can probably be extrapolated to a limited extent.

In case it is found that the empirical curve cannot be represented by an equation of the form of (27), then (28) is to be tested in a manner analogous to that just described.

Exp. 3. The Construction and Test of Thermoelectric Couples

THEORY OF THE EXPERIMENT. — Read Arts. (14–19), 24. If both the wires composing a thermoelectric couple are homogeneous, no electromotive force will be developed unless the two junctions are at different temperatures, whatever temperature difference there may be at points between the junctions. But if in either wire there be inhomogeneity, chemical or physical, an electromotive force will be developed when the region of inhomogeneity is at a temperature different from that of the remainder of the wire. For example, an unhomogeneous alloy, and also a wire that is softer at one place than at another, will give rise to parasitic currents when ununiformly heated. Again, some substances undergo allotropic transformation when raised to certain temperatures. For example, iron heated to 750° C. and nickel heated to 380° C. undergo changes that persist when cooled to ordinary temperatures.

For these reasons wires used for thermoelectric couples must be chemically and physically homogeneous and must not suffer allotropic transformation at temperatures within the range for which the couple is to be used. The object of this experiment is to construct a number of base metal thermoelectric couples, to

test them for homogeneity and freedom from allotropic changes, and to calibrate them against a standardized couple.

MANIPULATION. — For each half of a couple use a wire about one meter long and wrap it with a close spiral of asbestos string to within about three centimeters of each end. This can be most conveniently done by means of a lathe or other simple rotating device. Paint the asbestos covering with a paste consisting of 100 parts of silica flour, 50 parts of sodium silicate and 20 parts of burnt fire clay. Heat the wires thus prepared in a tube furnace till the paste has thoroughly hardened. Place side by side the two wires designed to constitute one couple and twist one pair of ends so as to form a close joint one to two centimeters long.

The twisted ends may be fused together by inserting them in the flame of an oxyhydrogen or an oxyacetylene blowpipe, an electric arc, or as follows. Connect one pole of a 110-volt circuit to the untwisted ends of the couple, and connect the other pole to a copper or carbon rod one centimeter or more in diameter. On causing the end of the twisted joint to approach the rod, an arc will be formed which will fuse together the ends of the wires of the couple. Under no circumstances should one watch the fusing operation with unprotected eyes. One should either use smoked glass goggles, or have between the eyes and the work a screen of smoked glass or one consisting of blue and red glass.

The thermoelectric couple is now ready to be tested and calibrated. To test a couple for homogeneity, connect the terminals to a galvanometer, immerse the junctions in a water or ice bath, and slowly pass the flame of a Bunsen burner along the length of the couple. If no change of deflection is produced, the wires of the couple are homogeneous.

To calibrate a number of couples, all of the hot junctions, together with the hot junction of a standardized couple, are placed in the middle of a tube furnace. The cold junction of the standard couple is maintained at the temperature at which it was calibrated, and the temperature of the cold junctions of the other couples is to be maintained at a temperature as nearly constant as possible. For this purpose may be used a bath of melting ice.

Readings of the electromotive force generated by each couple are now to be taken for a series of furnace temperatures. As commercial base metal couples have higher electromotive forces than a platinorhodium couple, it will be necessary to use a higher resistance in series with the base metal couples than that in series with the standard couple. For this experiment a millivoltmeter and switches arranged as in Fig. 32 will be convenient. In this
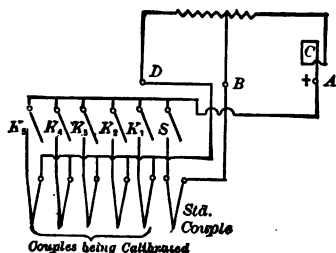
FIG. 32.

diagram, C is the moving coil of a sensitive millivoltmeter, A, B are the terminals of the low resistance coil of the millivoltmeter and A, D are the terminals of the high resistance coil. Some instruments are provided with a device by means of which the pointer can be clamped while the instrument is being moved. To release the pointer the milled

head is rotated till the pointer swings freely. On closing the switch S, connected to the standard couple, the electromotive force generated by this couple will be impressed on the millivoltmeter. On opening this switch and closing the switch K_1, connected to the first base metal couple, the electromotive force generated by this couple will be indicated on the millivoltmeter. Thus the electromotive force generated by any one of the couples can be measured.

In order that during the time an observation is being taken the temperature of the furnace may be fairly constant, it will be necessary to open the furnace switch a couple of minutes before observations are taken. Proceed as follows: When the furnace is at about 200°, open the furnace switch, wait till the temperature becomes constant, and then in quick succession take millivoltmeter readings with the standard couple, couple No. 1, the standard, couple No. 2, the standard, couple No. 3, etc. Note the temperatures of the cold junctions of the base metal couples as indicated by a mercury-in-glass thermometer. Close the switch, wait till the temperature is about 300° C., and then in quick

succession take readings with the standard couple, couple No. 1, the standard, couple No. 2, the standard, as before. Note the temperature of the cold junction of the base metal couples. Continue at 50° intervals throughout the range required. While the furnace cools, take readings at 50° intervals.

Tabulate the observed data as follows:

COLD JUNCTIONS AT 0° C.

Standard millivolts.	Couple No. 1 millivolts.	Standard millivolts.	Couple No. 2 millivolts.	Standard millivolts.	Couple No. 3 millivolts.	Standard millivolts.

Find the mean of the two electromotive forces developed by the standard couple before and after each reading of the base metal couples. From a previously determined calibration curve of the standard couple find the temperature corresponding to each of these means. Take these values as the furnace temperatures at the time the various base metal couple readings were made.

Tabulate the furnace temperatures and the electromotive forces of the various base metal couples. With furnace temperatures as abscissas and electromotive forces as ordinates, construct on one pair of coordinate axes a calibration curve for each base metal couple.

By means of the method described in the preceding experiment, find the equation of some one of these calibration curves. From this equation compute the electromotive forces corresponding to a series of assumed hot-junction temperatures. On a second sheet of cross-section paper construct the computed curve and also the empirical curve on which it is based.

Exp. 4. Determination of Temperature by Means of a Thermoelectric Pyrometer with the Cold Junction not Maintained at a Constant Temperature

THEORY OF THE EXPERIMENT. — Read Arts. (24, 25). It often happens that a thermoelectric couple calibrated with the cold junction at a known constant temperature is afterward used under conditions in which the cold junction cannot be maintained at a constant temperature. If the equation of the calibration curve of the thermoelectric couple is known at any definite cold-junction temperature, the correction to be applied to the indicated temperature when the cold junction is at any definite temperature can be determined by the method described in Arts. 25˙ and 26. The object of this experiment is to obtain a series of temperature observations from a calibrated thermoelectric pyrometer when the temperature of the cold junction is known but variable, and then to determine the actual temperatures corresponding to the observed values.

MANIPULATION. — Insert in an electric tube furnace the hot junction of a couple in connection with a direct-reading indicator and also the hot junction of a standard couple. The cold junction of the standard couple is to be maintained at 0° C. by means of a bath of melting ice. No attempt is to be made to maintain constant the temperature of the cold junction of the test couple, but its temperature is to be obtained by means of a mercury-in-glass thermometer.

At about 200° C. note in quick succession, the millivolts produced by the standard couple, the reading of the instrument connected to the test couple, the millivolts produced by the standard couple and the temperature of the cold junction of the test couple. Take similar observations at 100° intervals throughout the range of the test couple. In this experiment all electromotive forces are to be measured by means of a potentiometer, Arts. 20 and 21.

By the method described in Arts. 24 and 25, compute the temperature corresponding to the indicated temperature of the test

couple. From the calibration curve of the standard couple note the actual temperatures.

All the data, observed and computed, should be arranged systematically in a table. In the column next to the last put the computed temperatures, and in the last column put the temperatures obtained from the standard couple.

Exp. 5. Determination of the Transformation Points of a Specimen of Steel

THEORY OF THE EXPERIMENT. — Read Arts. (14–19). Many substances undergo a transformation into a different condition when they are subjected to a certain temperature. Such a transformation is accompanied either by an evolution or an absorption of heat. The temperatures at which these transformations occur are called "transformation points" or "critical points." Some substances have several transformation points. Transformation points are observed in the case of metals that have different allotropic forms, alloys, salts that have different amounts of water of crystallization, and solutions that have different amounts of water of hydration. When iron or steel passes through certain of its transformation points the hardness, coarseness of grain, and magnetic properties are considerably altered. The properties of steel acquired at any temperature can be made permanent by sudden quenching. The temperature at which a given specimen of steel may be quenched in order that the required properties may be fixed is determined by the transformation points of the specimen. In the heat treatment of steel the most important transformation point is that at which the grain is the finest and is the point at which the specimen should be quenched in order that the hardness may be a maximum. This temperature is called the "decalescent point."

If heat be gradually added to a specimen of steel all of the energy absorbed will be used in raising the temperature of the specimen, until the temperature is about 750° C. At this point some of the energy absorbed will be used in producing internal molecular changes. This transformation point is known as the "Ac_1 point."

When the specimen acquires a temperature in the neighborhood of 800° C., all of the energy absorbed at that temperature will be used in producing internal changes. This transformation is exhibited by a sudden cessation of the rise in temperature of the specimen. This transformation point is known as the "Ac_2 point," or the "decalescent point." A third transformation called the "AC_3 transformation" takes place from about 800° C. to 875° C., depending upon the carbon content. These three points are known as "decalescent points." Of these, the AC_3 is of most importance as it is the temperature at which steel changes in size of grain and in magnetic properties.

On cooling the specimen, a series of reverse changes takes place but at different temperatures, These transformations are accompanied by an evolution of heat which is exhibited by increases in temperature. The transformation points of the cooling specimen analogous to the decalescent points are called "recalescent points." They are usually denoted by Ar_1, Ar_2, and A_3.

The object of this experiment is to determine the transformation points of a specimen of steel.

MANIPULATION. — On very slowly heating a specimen of steel there is such a sudden interruption in the rise of temperature at the decalescent point, and on very slowly cooling the specimen there is such a sudden interruption in the fall of temperature at the recalescent point, that those two points can be readily observed by an ordinary thermoelectric pyrometer. To locate the other transformation points a more sensitive method is required. A method that can be applied to the location of all the transformation points will now be described.

The specimen of steel and a piece of some metal such as nickel that does not exhibit transformation points within the range of transformation points of steel are placed together within an electrically heated furnace. The terminals of a rhodioplatinum couple AC, Fig. 33, are joined to a millivoltmeter V. This thermoelectric pyrometer indicates the temperature of the steel specimen. A second couple BDG consists of a short length of rhodioplatinum alloy BD joined to two lengths of pure platinum

wire. The junctions A and B are at the temperature of the steel specimen, and the junction D is at the temperature of an adjacent piece of nickel.
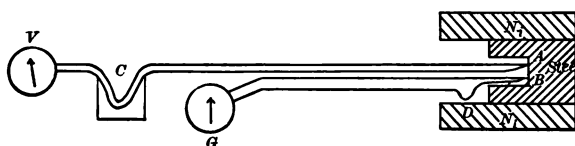
FIG. 33.

So long as the steel and the nickel are at the same temperature, the sensitive galvanometer G will be undeflected. But when a molecular transformation of the steel occurs, there will be either an evolution or absorption of heat by the specimen, and the galvanometer G will be deflected. In this arrangement, the galvanometer G serves as a sensitive indicator of the presence or
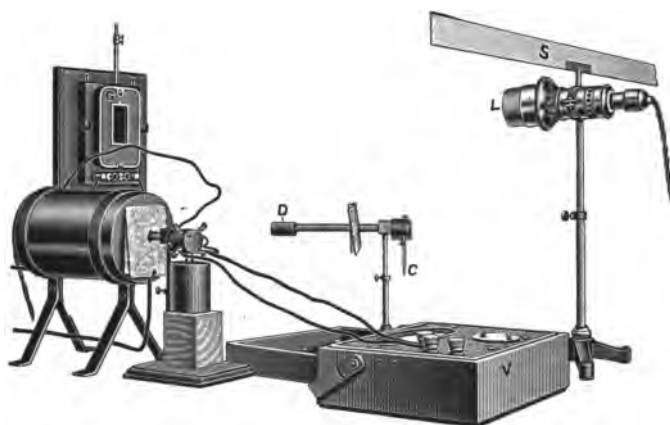
FIG. 34.

absence of molecular transformation, while the millivoltmeter V serves to indicate the temperature of the specimen.

The first time the apparatus is used, it will be necessary to run a preliminary experiment in order to determine the setting of the furnace rheostat to give the proper rate of heating, and in order that the resistance in series with the galvanometer may

have the value that will give the galvanometer the maximum sensitiveness consistent with the requirement that at no time shall the deflection be beyond the limits of the scale. Place the sample, properly connected to the two thermoelectric couples, within the furnace and adjust the furnace rheostat till the temperature will rise to about 800° C. in 45 minutes. Put sufficient resistance in series with the galvanometer that the deflection produced at the decalescent point will remain on the scale.

In performing an experiment, connect up the apparatus, place the cold junction C in a bath of melting ice, set the furnace rheostat at the predetermined position, close the furnace switch, and when the temperature of the specimen has reached about 600° C., start taking simultaneous readings of the millivoltmeter and galvanometer. These readings should be taken at 10° C. intervals to a temperature thirty or more degrees above the decalescent point. Then open the furnace switch and continue taking simultaneous readings at 10° C. intervals while the specimen cools to about 600° C. After having started to take readings do not alter the setting of the furnace rheostat.
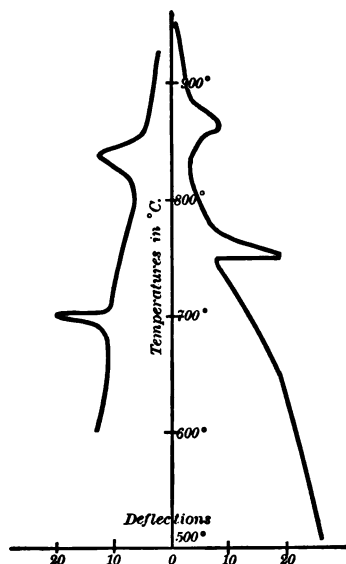
Fig. 35.

With temperatures as ordinates and galvanometer deflections as abscissas, plot a heating curve and a cooling curve of the specimen. A typical pair of curves is shown in Fig. 35. From an inspection of this curve point out the various transformation points and the ranges through which the transformations extend.

CHAPTER IV

RADIATION PYROMETRY

29. The Experimental Realization of Black-body Radiation. —
Though no known substance fulfills the definition of black-body,
Kirchhoff has shown that black-body radiation can be experi-
mentally realized. Let A, Fig. 36, represent an ideal black-body
within a uniformly heated athermanous
enclosure, and in thermal equilibrium with
it. Being in thermal equilibrium with
its surroundings it radiates to the walls
of the inclosure the same amount of
energy it receives from them. Since it
radiates to the wall behind it the same amount of energy it re-
ceives from that wall, to an observer at O, the body and the
background are equally bright. Therefore, the walls of a
uniformly heated athermanous enclosure radiate as an ideal
black-body. If a small aperture be made in the enclosing wall,
the radiance that will emerge from the enclosure will be that of a
black-body.

In the succeeding pages a uniformly heated athermanous en-
closure will be called a "black-body" with quotation marks. The
production of black-body radiance from the interior of a heated
enclosure requires (a) that the temperature of the enclosure be
uniform throughout, (b) that the walls of the body be athermu-
nous, (c) that all frequencies of black-body radiance be present,
(d) that all radiance be due to temperature — no luminescence
effects.

It can thus be shown that any body within a uniformly heated
enclosure and in thermal equilibrium with its surroundings,
radiates like a black-body. Suppose the same enclosure contains

FIG. 36.

71

a body B, Fig. 36, which has a transmitting factor and an absorptive factor of any value. Since the body is assumed to remain in thermal equilibrium with its surroundings, it is receiving energy from all directions and is emitting energy in all directions at the same rate. An observer at O, will receive energy at the same rate from elements of area of the body and from elements of the enclosing walls. Consequently, the surface of the body radiates like a black-body. A black-body is sometimes called a "complete radiator" or "integral radiator."

The bore of an uniformly heated tube, long compared with its diameter, emits radiance that is essentially the same as that from an ideal black-body. As nearly uniform temperatures as may be desired can be secured by electric heating. Two methods of electric heating are in vogue. The first consists in the use of an

FIG. 37.

electric current in a spiral conductor of high resistance and high melting point wrapped closely about the tube to be heated, Fig. 37. The temperature is regulated by varying the resistance in circuit with the heating coil. For temperatures up to 1100° C. the alloy called "nichrome II," is available; for temperatures up to 1500° C., platinum can be used. The temperature of the ends

of the tube may be kept at the same as that of the middle by having about the ends of the tube more turns of conductor per unit length of the tube, than about the middle. In case the ends are at a different temperature than the middle of the tube, the de-

FIG. 38.

parture from black-body radiation can be diminished by the use of perforated diaphragms placed inside the tube near the ends.
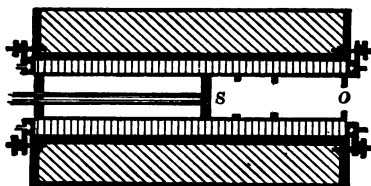
The uniformity of temperature along the axis of the tube can be tested by means of a thermoelectric pyrometer. An electric furnace that is more robust under protracted use at high tempera-

tures consists of a refractory tube on which is strung a column of thin graphite discs, Fig. 38. The end discs are joined to the low potential terminals of a step-down transformer connected in series with an ammeter. By altering the pressure between the graphite discs by means of a pair of hand screws, the electric resistance of the graphite column can be altered, and thereby the temperature of the axial tube.

For use as a "black-body," a current-carrying carbon furnace has one point of inferiority as compared with a current-carrying wire furnace in the great difficulty in maintaining a constant temperature. This is due to the fact that the resistance of carbon diminishes with an increase of temperature, whereas the resistance of the metals used in furnaces increases with an increase of temperature. With a metal-wound furnace, the temperature can be maintained at a nearly fixed value by adjusting the resistance in circuit till the current is such that the heat produced in the furnace equals the heat dissipated by radiation, conduction, and convection. With a carbon furnace, if the resistance in circuit be increased, the lower current will also be accompanied by a decrease in temperature. But this decrease in temperature by causing an increase in the resistance of the carbon will cause a further decrease of current, and this, in time, a further decrease of temperature. This action will then be repeated.

30. The General Principles of Radiation Pyrometry. — The fact that the rate with which a black-body radiates energy is a function of the thermodynamic temperature (Art. 7), is the basis of a valuable system of high temperature measurement called "Radiation Pyrometry." In this system, radiance of all frequencies emitted by the source is allowed to impinge on a distant absorbing body of small size and thermal capacity. The rise in temperature of the absorbing body is a measure of the rate with which energy is incident upon it, and this of the temperature of the source.

In the radiation pyrometers now in successful use, radiance is concentrated by means of a collective lens or mirror upon a small and sensitive temperature measuring device such as a thermo-

junction in connection with a millivoltmeter. Radiance of all
frequencies, visible and invisible, incident on a lampblack-coated
junction of such a thermoelectric element will be almost entirely
absorbed and transformed into heat. This heat will raise the
temperature of the receiving junction by an amount proportional
to the energy absorbed, thereby producing an electromotive force
of a value depending upon the difference in temperature of the two
junctions of the element. Thus, if the fraction of the total inci-
dent energy absorbed by the receiving surface were constant, the
indications of the millivoltmeter would show the rate with which
energy is radiated by the source.

It is found that the fraction of the total incident energy that
is absorbed by the receiving surface is not a constant fraction for
all temperatures, but that it is a function of the temperature of the
radiating source. In fact, experiment shows that when a lamp-
blacked thermoelement is exposed to radiance from a black-body
at thermodynamic temperature T, there is developed an electro-
motive force E of the value

$$E = aT^b, \qquad (29)$$

where a and b are constants for any particular instrument. These
constants can be found from the observation of the electromotive
forces developed when the instrument is exposed to the radiance
from a black-body at two known temperatures.

After these constants are determined, the above equation can
be employed to determine the thermodynamic temperature of any
substance that radiates like a black-body. But the application
of this method to a substance that does not radiate like a black-
body would not give thermodynamic temperatures. For example,
if a piece of black carbon, one of polished platinum, and one of
transparent glass be placed within a "black-body," as in Fig. 36,
then after the system has attained thermal equilibrium all three
bodies are at the same thermodynamic temperature. And since
all three bodies are radiating at the same rate, they are at a com-
mon black-body temperature. If the three specimens be quickly
removed from the enclosure they will radiate at quite different

rates. The carbon will radiate about as before, the platinum at a much less rate, and the glass will radiate scarcely at all. That is, though all three bodies are at the same thermodynamic temperature, they are now at quite different black-body temperatures. A radiometer actually indicates black-body temperatures. But when the body being studied radiates as a black-body, its black-body temperature equals its thermodynamic temperature.

31. The Féry Thermoelectric Mirror Radiation Pyrometer. — This instrument consists of a concave gold-plated mirror M, Fig. 39, and a small thermoelectric couple T, connected to a milli-voltmeter by means of binding posts BB'. By means of a rack and pinion P, the concave mirror can be moved till the image of the source is on one junction of the thermocouple.

This focalizing is facilitated by an eyepiece E, in front of an aperture in the concave mirror, together with two semicircular plane mirrors m mounted in the thermocouple box. A semicircular notch in the middle of the straight side of each plane mirror permits the passage of radiance reflected from the concave mirror to reach the thermojunction. These semicircular plane mirrors are inclined to one another at an angle of about 5°, Fig. 40. When the aperture in the semicircular mirrors is in the plane of the image of the source sighted upon, the image seen in the eyepiece is unbroken. When in this position, the image of an incandescent lamp filament would appear as in Fig. 41. When the image formed by light after reflection from the mirror M, Fig. 39, is either in
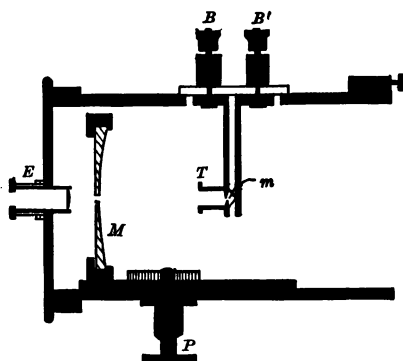
FIG. 39.

FIG. 40.   FIG. 41.   FIG. 42.

front of or behind this aperture, the image seen in the eyepiece is broken into two halves, one half being displaced to the right and the other to the left as in Fig. 42. In Fig. 43 the Féry Thermo-electric Mirror Pyrometer E is shown in connection with the milli-voltmeter G.
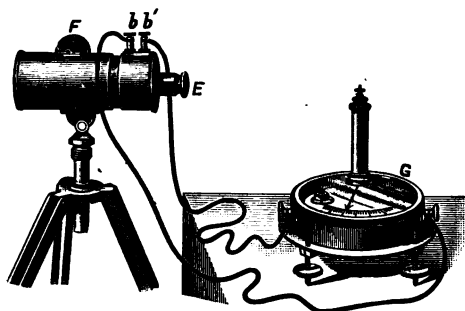
FIG. 43.

It will now be shown that to a close degree of approximation, the rate with which radiance is received by the thermojunction of a Féry Thermoelectric Pyrometer is independent of the distance of the focalized instrument from the source.
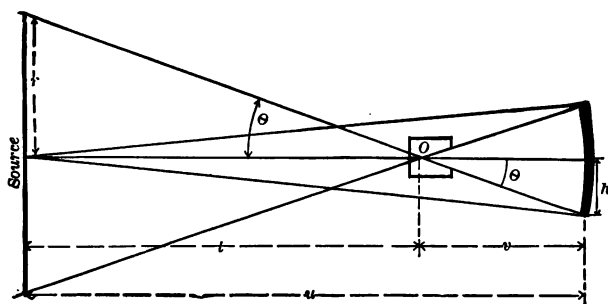
FIG. 44.

Let J represent the rate of incidence of radiance on the thermo-couple; I the rate with which energy is emitted from unit area of the source; A_0, the area of the part of the source from which radiance reaches the thermocouple; A_i, the area of the image of

A_0; u, the distance from the source to the mirror; v, the distance from the image to the mirror.

Now the total radiance incident on the thermocouple is proportional: (a) to the rate with which energy is emitted from unit area of the source; (b) to the area of the part of the source from which radiance reaches the thermocouple; (c) inversely proportional to u^2; (d) proportional to the aperture of the mirror. That is,

$$J \propto \frac{IA_0h^2}{u^2}.$$

But from a property of spherical mirrors,

$$\frac{A_0}{A_i} = \frac{u^2}{v^2}.$$

Consequently,

$$J\left[\propto \frac{IA_0h^2}{u^2}\right] \propto \frac{IA_i\, u^2}{v^2}\frac{h^2}{u^2} \propto \frac{IA_ih^2}{v^2} \propto IA_i\tan^2\theta,$$

or,

$$\frac{J}{A_i} \propto I \tan^2\theta.$$

In the Féry Mirror Radiation Pyrometer, θ is maintained constant by means of a system of diaphragms in the thermocouple box. Therefore, the above variation reduces to

$$\frac{J}{A_i} \propto I. \qquad (30)$$

That is, under the conditions expressed and assumed in the above discussion, the rate with which radiance is incident on the thermocouple of the Féry Mirror Thermoelectric Radiation Pyrometer is proportional to the intensity of the radiating source and is independent of the distance between the source and the focalized instrument. In this discussion it has been assumed: (a) that the image of the source is not smaller than the absorbing surface; (b) that the angle θ, Fig. 44, remains constant. The dimensions of the industrial form of the instrument are such that these two conditions are realized to a close degree of approximation when the distance from the source to the focalized instrument

exceeds one meter, and when at the same time the radiating source is so large that its image covers the mirror at the ends of the thermocouple.

The relation between the radius r of the source and the distance l from the source to the thermocouple, Fig. 44, is

$$\tan \theta = \frac{r}{l},$$

in which θ is a constant for any particular instrument determined by the focal length of the converging mirror and the aperture of the thermocouple box.

For sources of small temperature, the instrument is used with the receiving end entirely open. But if the aperture AA' were entirely open when sighted on sources of high temperature, the millivoltmeter might be deflected beyond the end of the scale and the thermoelectric junction might even be injured by the high temperature of the image. To guard against these dangers, when employed to measure high temperatures, the aperture is partially closed by a sectored diaphragm, Fig. 52, which cuts off a definite fraction of the incident radiance.

The millivoltmeter can be divided so as to indicate temperatures directly. Two scales are usually provided, one for use when the receiving end is open, and another for use when partially closed by the sectored diaphragm. Commercial instruments of the Féry Mirror type are constructed with a range from 600° to 1500° C. and over.

Usually the principal focal length of the concave mirror is 7.6 cm., and the diameter of the aperture of the diaphragm of the thermoelectric couple box is 0.15 cm. For an instrument having these constants the following table gives the diameter of source required for various distances of l between source and receiver.

Distance from source to receiver, cm.	Diameter of source, cm.
80	1.4
100	1.8
150	3.1
200	4.2
300	6.3
500	10.7

32. The Relation between the Energy Rate at a Point and the Distance from the Source. — The radiance incident at a point is directly proportional to the effective area of the radiating surface and inversely proportional to the square of the distance between the emitting surface and the receiving body. Thus if a diaphragm D, Fig. 45, be placed in front of a radiating surface S, then with respect to a point O, at a distance l, the area of the radiating surface is A. Whence the energy per unit time, J, incident on O, is expressed by the equation
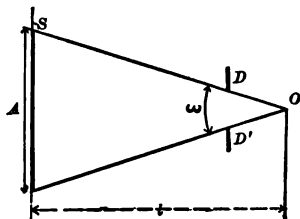
Fig. 45.

$$J = k\frac{A}{l^2}$$

where k is a coefficient of proportionality. If the distance l be large compared with the diameter of the effective area A, then $\dfrac{A}{l^2}$ measures the solid angle subtended at O, by the surface sending energy to O. Representing this solid angle by the symbol ω

$$J = k'\omega.$$

That is, so long as the solid angle subtended by the source at the receiving point is constant, the rate with which radiance is incident at the receiving point is independent of the distance between the source and the receiving body.
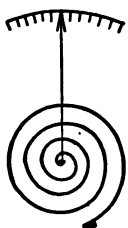
Fig. 46.

33. The Féry Spiral Pyrometer. — This instrument is the same as Féry's Thermoelectric Mirror Pyrometer except that in place of the incident radiance being reflected to one junction of a thermoelectric couple, the incident radiance is reflected to a small blackened spiral, Fig. 46, which will coil or uncoil as the temperature of the spiral is increased or decreased. This sensitive spiral consists of a double ribbon of two metals of different thermal expansion coefficients. The two ribbons being fastened together throughout

their length, an increase in temperature, by causing one of the ribbons to expand more than the other, will result in the spiral coiling up more closely. The end of the double strip at the center of the spiral is attached to a shank on which is mounted a pointer that moves over a circular scale as the spiral coils or uncoils. This scale is empirically graduated to indicate temperatures.

When the instrument is placed in front of a hot body the spiral will be quickly heated and the whole case will be slowly raised in temperature. There will thus be produced a slow creep of the pointer superposed on a sudden deflection. In using the instrument, the reading should not be taken till the slow creep has ceased. As the Féry Spiral Pyrometer requires no millivoltmeter or other accessory apparatus it is much more portable than the Thermoelectric Mirror Pyrometer.

Fig. 47.

34. Fixed Focus Radiation Pyrometers. — Any radiation or optical pyrometer should give the same indication when the distance from the source is altered through considerable limits. This requirement will be met if the cone of light incident on the receiving device is of a constant solid angle. The constancy of this solid angle can be maintained: (*a*) by a diaphragm in combination with a concave spherical mirror focalized on the source as in the Féry Thermoelectric Mirror Radiation Pyrometer (Art. 31); (*b*) by a diaphragm in combination with a converging lens focalized on the source (Art. 42); (*c*) by a diaphragm in combination with a converging spherical lens or mirror focalized on the aperture of the diaphragm, Fig. 48; (*d*) by a diaphragm in combination with a conical mirror, Fig. 49. Instruments designed according to the latter methods have the various parts fixed relative to one another and are called Fixed Focus Pyrometers.

From an inspection of Fig. 48 it will be seen that so long as the source is not too small to subtend the solid angle formed by the

cone having O as apex, and tangent to the orifice in the diaphragm AA', the rate with which radiance is incident on the receiving device T is independent of the distance from the source to the instrument, Art. 32.   This rate is the same that would exist if a portion of the source the size of AA' were placed in the orifice of
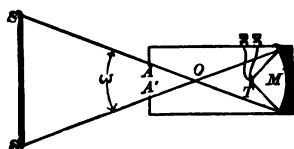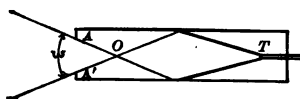
FIG. 48.   FIG. 49.

the diaphragm.   For this reason a fixed focus instrument can be produced by having the end diaphragm, and the receiving device, at the conjugate foci of a mirror or lens.

Instead of a concave spherical mirror, a conical mirror may be employed as shown in Fig. 49.   In this case no image of the object is formed, but the energy incident on the receiving device T is the same as it would be if the orifice in the end diaphragm were filled by a portion of the source.

The millivoltmeter used in connection with a fixed focus thermoelectric radiation pyrometer can be provided with a recording device by means of which a permanent record can be made of the history of a temperature change.

35. The Foster and the Brown Fixed Focus Pyrometers. — These instruments differ from the Féry Thermoelectric Mirror Pyrometer in that the tube is longer, and the image formed on the thermojunction is of the orifice at the end of the instrument and not of the hot object whose temperature is sought.   That is, the disc, T, attached to the thermojunction, and the aperture AA', Fig. 48, are at the conjugate foci of the mirror M.

The object, mirror, and thermocouple being in fixed positions, the focalizing rack and pinion of the Féry instrument is dispensed with.   By this device the angle θ, Fig. 44, is constant so long as the angle ω, Fig. 48, is subtended by the source.   Thus, so long as the solid angle subtended by the source at the point O, is

constant, the rate with which radiance is incident on the thermojunction is independent of the distance between the source and the instrument. A millivoltmeter connected to the thermocouple indicates the temperature of the source. In using the commercial forms of this instrument, the distance of the point O, from the source must not exceed ten times the diameter of the source.

Fig. 50.

The range of temperatures that can be measured by the instrument is modified by the diameter of the aperture AA'. For bodies at very high temperatures this aperture is small; for bodies at lower temperatures this aperture is large. The same millivoltmeter can be used in connection with apertures of different sizes, either by having a separate scale for each aperture, or by having a single scale and using a different multiplying factor for each aperture.

The Brown pyrometer differs from the Foster, Fig. 50, in that the tube is made collapsible for convenience of carrying, and a finder is attached to the tube for convenience in directing the instrument toward the source whose temperature is sought.

36. Thwing's Fixed Focus Radiation Pyrometer. — In place of the gold-plated spherical mirror employed by Féry and Foster, Thwing has adopted a concave conical metal reflector M, Fig. 49, in the apex of which is placed the thermoelectric junction T connected to a millivoltmeter.

When pointed at a hot body, practically all of the radiance entering the aperture AA' will, after multiple reflection from the sides of the conical mirror, reach the thermoelectric junction. So long

as the solid angle ω is subtended by the body whose temperature is sought, the rate with which radiance is incident on the thermoelectric junction is constant. The instrument, therefore, requires no focusing. In using the standard form of this instrument, the distance of the point O from the source must not exceed twelve times the diameter of the source. There is no limit to the nearness with which the Thwing Pyrometer may be placed to the hot body except the danger of injury due to excessive temperature.

FIG. 51.

The range of temperature that can be measured by the instrument is modified by the diameter of the aperture AA'. For bodies at very high temperature, this aperture is small; for bodies at lower temperatures this aperture is large. The same millivoltmeter can be used in connection with apertures of different sizes, either by having a separate scale for each aperture, or by having a single scale and using a different multiplying factor for each aperture.

As the metal mirror tarnishes, the Thwing instrument must be frequently recalibrated.

37. Radiation Pyrometers Indicate Black-body Temperatures. — It should be kept in mind that radiation pyrometers indicate black-body temperatures. Only when a body is radiating under black-body conditions is its black-body temperature equal to the thermodynamic temperature. For bodies of the same radiating power, the black-body temperatures will be equal when the thermodynamic temperatures are equal. But for bodies of different radiating power, the black-body temperatures will not be the same when the thermodynamic temperatures are equal. Only for a body of constant radiating power will the ratio of two

black-body temperatures be equal to the ratio of the thermodynamic temperatures. A stream of melted iron has a black-body temperature less than that of the same iron when sufficiently cooled to be covered by a coating of slag or oxide.

A uniformly heated opaque enclosure and a body within such an enclosure radiates as a black-body. The actual or thermodynamic temperature of a furnace can be obtained by directing a radiation pyrometer into a tube closed at one end that projects into the region whose temperature is desired.

38. Precautions in Using Radiation Pyrometers. — The receiving instrument is subject to certain faults that should be noted. After directing a radiation pyrometer toward a hot source, a certain time is required for the full indication to be developed. With different instruments of the same model this lag may vary from 20 seconds to 10 minutes. In instruments of a different model the lag may be less than 5 seconds. In the case of some pyrometers the deflection rises to a maximum and then gradually diminishes to a fixed value. In using an instrument one should take the maximum reading. For the determination of temperatures that are not constant an instrument must be used that has a very small time lag.

The lag is due to the heat capacity and thermal conductivity of the receiver. The drop after the maximum deflection is due to conduction of heat away from the receiver, and in the case of a thermoelectric receiver, to reradiation and to conduction to the cold junction.

The lag of the Féry radiation pyrometers is too great to permit their use for the determination of rapidly varying temperatures. In the Thwing instrument the lag is lower than in any other.

After the instrument has been calibrated, the mirror surface must be maintained constant. Dirt can be removed with a camel's-hair brush. If the mirror becomes tarnished the instrument must be recalibrated.

In the use of a Féry Thermoelectric Mirror Radiation Pyrometer serious error will result if the area of the part of the focalizing

mirrors covered by the image is not the same as when the instrument was calibrated. This is due to the difference in the heat absorbed by the focalizing mirrors. If when the instrument is directed toward a body of certain temperature, a larger area of the focalizing mirrors be covered by the image, than when the instrument was calibrated, the hot junction will be higher in temperature, and the electromotive force developed by the thermocouple will be greater than they would be if the instrument were used under the conditions existing at the time of the calibration. The indicated temperature will then be too high. The relation between the fractional error in the temperature and the fractional error in the electromotive force is readily obtained from (29). Differentiating, we have

$$dE = abT^{b-1} dT. \tag{31}$$

Dividing each member of this equation by the corresponding member of (29), we obtain

$$\frac{dE}{E} = b \frac{dT}{T}. \tag{32}$$

Since the value of b is always about 4, this equation shows that the fractional error in the absolute temperature is about one-fourth of the fractional error in electromotive force.

Lack of attention to this point may readily produce an error of 10 to 20 per cent in the temperature determination. The error may be obviated by placing the instrument at such a distance from the source that the sharp image of the source entirely covers the focalizing mirrors.

Exp. 6. Calibration of a Radiation Pyrometer

THEORY OF THE EXPERIMENT. — Read Arts. 29, 30, 37 and the article describing the particular type of pyrometer under test. Any radiation or optical pyrometer can be calibrated by a step-by-step comparison of the pyrometer readings with the readings of a standardized thermoelement in a "black-body" whose temperature can be varied through the range for which the pyrometer

is to be used. In the case of a thermoelectric radiation pyrometer exposed to the radiance from a black-body, the relation between the thermodynamic temperature of the body and the electromotive force developed is given by (29),

$$E = aT^b, \qquad (29')$$

where a and b are constants for the particular instrument. The determination of these constants require a black-body at two known temperatures.

The object of this experiment is to calibrate by the step-by-step method, and also by means of (29) and two known temperatures, a thermoelectric radiation pyrometer provided with an indicator reading in millivolts and in degrees of temperature. The definite equation of the temperature-electromotive force curve is to be determined, the curve represented by this equation constructed, the empirical calibration curve constructed, and also the curve coordinating indicated temperatures and corresponding corrections.

MANIPULATION. — The apparatus used for the calibration includes a complete radiator, that is, a "black-body," together with a standardized thermoelement, in connection with a suitable millivoltmeter.

In using an electric tube furnace as a "black-body," Figs. 37 and 38, one junction of a rhodioplatinum thermocouple is mounted in a septum S of porcelain or graphite situated at the center of the tube, while the other junction JJ' of the couple is immersed in a bath of melting ice.

After surrounding the "cold junction" JJ' with melting ice, Fig. 52, close the main switch W, and regulate the current till the millivoltmeter Vm indicates a temperature somewhat lower than the lowest one desired for the calibration. On opening the switch, the temperature will continue to rise. Place the pyrometer being calibrated in front of the aperture O, and with the axis of the pyrometer coinciding with the axis of the furnace. The distance between the "black-body" and a Féry Thermoelectric Mirror Radiation Pyrometer must be such that the focalizing mirrors are entirely covered by the image. In the case of the Féry Spiral

Pyrometer, the spiral must be covered by the image. In the case of the fixed focus pyrometers, the solid angle at the pyrometer subtended by the septum in the furnace must not be less than the angular aperture of the instrument. In this last case the maximum allowable distance may be obtained by moving the pyrometer toward the orifice of the "black-body" till the pyrometer reading does not increase with a further diminution of distance.
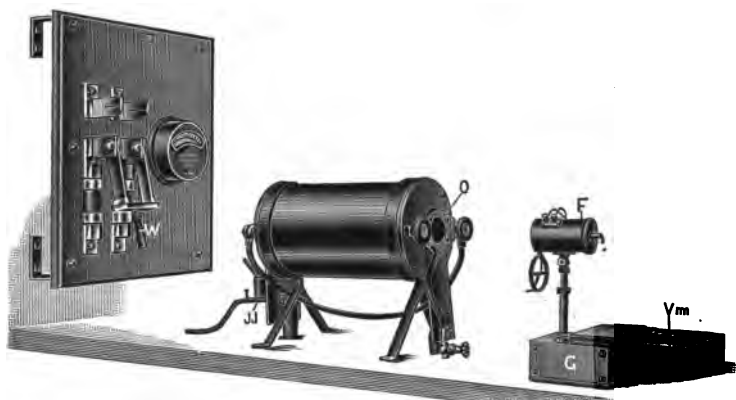
FIG. 52.

When the "black-body" has attained the lowest temperature to be included on the required calibration curve, take simultaneously the temperature reading of the thermoelectric pyrometer, the electromotive force reading and the indicated temperature reading of the radiation pyrometer. Since the temperature of the septum lags behind the temperature of the tube, one must take no reading till the thermoelectric couple indicates a constant temperature.

Again close the switch, increase the current in the electric furnace till the temperature is about one hundred degrees above the former temperature, open the switch, wait till the temperature is practically constant, and then take simultaneously readings on the two pyrometers as before.

Proceeding in this manner, take readings at temperature intervals of about 100° throughout the range for which the instrument is to be calibrated.

Construct a table of six columns, in the first column of which are given the electromotive forces as read from the radiation pyrometer indicator, in the second column the indicated temperature read from the same instrument, in the third column the electromotive forces read from the indicator connected to the standard thermocouple, in the fourth column the thermodynamic temperatures corresponding to these electromotive forces, in the fifth column the difference between the thermodynamic temperatures and the temperatures indicated by the instrument under test, and in the sixth column the temperature values computed by means of (29) in the manner now to be described.

With the data in column one as ordinates and the data in column four as abscissas construct the empirical calibration curve of the pyrometer under test. By substituting in (29) the coordinates of two points on this curve, the constants a and b could be determined.

These constants can be determined more accurately, however, from the equation in the form,

$$\log E = \log a + b \log T. \tag{33}$$

Using the coordinates of a series of points on the empirical calibration curve, plot a curve coordinating $\log E$ and $\log T$. If the observed data are correct, this curve will be a straight line. The intercept on the axis of ordinates equals $\log a$, and the ratio of the ordinate to the abscissa of any point equals b.

By substituting in (29) the values of a and b we obtain the definite equation of the calibration curve. Using this equation compute the values of E for a series of convenient values of T. Using these values plot the computed calibration curve of the instrument on the same sheet with the previously drawn empirical calibration curve.

With the data in column five as ordinates and the data in column four as abscissas plot the correction curve of the given pyrometer.

CHAPTER V

OPTICAL PYROMETRY

39. Kirchhoff's Law. — The ratio of the energy absorbed to the energy incident on a body is called the *absorptive power* of the body. An important relation between the absorptive power of a body and the rate with which it emits radiance was stated by Kirchhoff. As applied to monochromatic radiance it may be stated as follows: *The ratio of the rate of emission to the absorptive power is for all bodies the same function of wave-length and thermodynamic temperature.*

Thus representing the rate of radiation by I_λ, and the absorptive power by the symbol a,

$$\frac{I_\lambda}{a} = F\ (\lambda T).$$

For an opaque body, the sum of the radiance absorbed and the radiance reflected equals the radiance incident on the body. Calling the incident energy unity, we have for an opaque body

$$a + r = 1.$$

If the body be black, the reflected energy equals zero. That is, for a black-body,

$$a_b = 1.$$

Hence, $$\frac{I_\lambda}{a}\ [= F\ (\lambda T)] = \frac{I_{\lambda b}}{a_b} = I_{\lambda b}. \tag{34}$$

The *emissive power* of a body is the ratio of the rate of radiation of energy by it, to the rate of radiation of a black-body at the same thermodynamic temperature. Thus, representing the emissive power of any given body by the symbol e, we have,

$$e = \frac{I_\lambda}{I_{\lambda b}}. \tag{35}$$

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Comparing (34) with (35) we obtain

$$e = a. \tag{36}$$

That is, the emissive power of any body equals the absorptive power.

40. Wien's Distribution Law. — When the temperature of a luminous body is increased, not only is the total radiance increased but the brightness of every part of the spectrum is increased. The rate of radiation of energy I_λ, corresponding to visible radiance of wave-length λ, of a black-body at absolute thermodynamic temperature T, is expressed by Wien's Distribution Law,

$$I_\lambda = c_1 \lambda^{-5} e^{-\frac{c_2}{\lambda T}}, \tag{37}$$

where e is the base of the natural system of logarithms and c_1 and c_2 are constants the values of which can be found by measuring I_λ at two known thermodynamic temperatures for light of known wave-lengths.

Wien's Law is a special case of the general radiation law derived by Planck from purely thermodynamic considerations.

$$I_\lambda = c_1 \lambda^{-5} \left(e^{\frac{c_2}{\lambda T}} - 1 \right)^{-1}. \tag{38}$$

Planck's Law apparently applies with exactness for any wave-length and temperature. Wien's Law applies only to wave-lengths included within the visible spectrum, and to temperatures within the range that can be produced artificially. At 5000° absolute, the difference between the results obtained from Planck's Law and Wien's Law is about one per cent.

Wien's Distribution Law may be expressed in the form:

$$\log_{10} I_\lambda = \log_{10} c_1 - 5 \log_{10} \lambda - \frac{c_2 \log_{10} e}{\lambda T}.$$

Or, representing the constant quantity $(\log_{10} c_1 - 5 \log_{10} \lambda)$ by the symbol C_1, the constant quantity $\dfrac{c_2 \log_{10} e}{\lambda}$ by the symbol C_2

and the Brigg's or ordinary logarithm by "log" without subscript, this equation may be put into the abbreviated form:

$$\log I_\lambda = C_1 - C_2 \frac{1}{T}. \tag{39}$$

Experiment shows that when λ is expressed in microns,* $c_2 = 14,500$ (nearly).†

That is,

$$C_2 \left[= \frac{c_2 \log e}{\lambda} \right] = \frac{14,500 \ (0.4343)}{\lambda} = \frac{6297}{\lambda}. \tag{40}$$

41. The Thermodynamic Temperature corresponding to a given Black-body Temperature. — The number which represents the temperature of a black-body on the absolute black-body scale is that which represents the same temperature on the absolute thermodynamic scale. For a nonblack-body the number which represents the temperature on the black-body scale is less than the number which represents the same temperature on the thermodynamic scale. The difference depends upon the lack of complete absorptive power of the surface of the body.

A black-body temperature measured from the absolute zero in centigrade degrees by means of radiance of all frequencies emitted by the hot body is often represented by the symbol K, e.g., $1200°\ K$. And if measured by means of radiance of a single frequency it is represented by the symbol K_λ, where λ is the wavelength in air of the radiance. For example, $1200°\ K._{65}$ represents a black-body temperature measured by means of radiance of wave-length in air of 0.65 microns.

Consider a nonblack-body at a temperature according to the absolute black-body scale of $K_\lambda°$, and according to the thermodynamic scale of $T°$. The relation between T and K_λ will now be deduced.

* The micron is one-thousandth of a millimeter and is represented by the symbol μ.

† Other determinations of this constant give the values $c \doteq 14,250$ and 14,360.

Suppose the given nonblack-body be first within a uniformly heated opaque enclosure, and later be without the enclosure but the same thermodynamic temperature. When within the enclosure and in thermal equilibrium with it, the body is at some thermodynamic temperature T and is radiating energy of wavelength λ at the rate $I_{\lambda b}$, given by Wien's Distribution Law (39),

$$\log I_{\lambda b} = C_1 - C_2 \frac{1}{T}. \tag{41}$$

When at the same thermodynamic temperature, but outside of the heated enclosure, the same body is at some black-body temperature K_λ, and is radiating at a less rate I_λ, given by Wien's Distribution Law.

$$\log I_\lambda = C_1 - C_2 \frac{1}{K_\lambda}. \tag{42}$$

Subtracting from each member of (42) the corresponding member of (41) we obtain

$$\log\left[\frac{I_\lambda}{I_{\lambda b}}\right] = C_2\left[\frac{1}{T} - \frac{1}{K_\lambda}\right]. \tag{43}$$

By definition, the ratio of the rate of radiation of any body to the rate of radiation of a black-body at the same thermodynamic temperature is the emissive power of the given body. It has been shown (36) that the emissive power of any body equals the absorptive power. Consequently the above equation can be put into the form:

$$\log a = C_2\left[\frac{1}{T} - \frac{1}{K_\lambda}\right],$$

or,

$$\frac{1}{T} = \frac{1}{K_\lambda} + \frac{\log a}{C_2}.$$

On substituting for C_2 its value (40), we have

$$\frac{1}{T} = \frac{1}{K_\lambda} + \frac{\lambda \log a}{6297}, \tag{44}$$

where T denotes the absolute thermodynamic temperature that corresponds to the black-body temperature K_λ of a body that

absorbs radiance of wave-length λ at the rate a.   It should be noted that in this equation λ is expressed in microns.
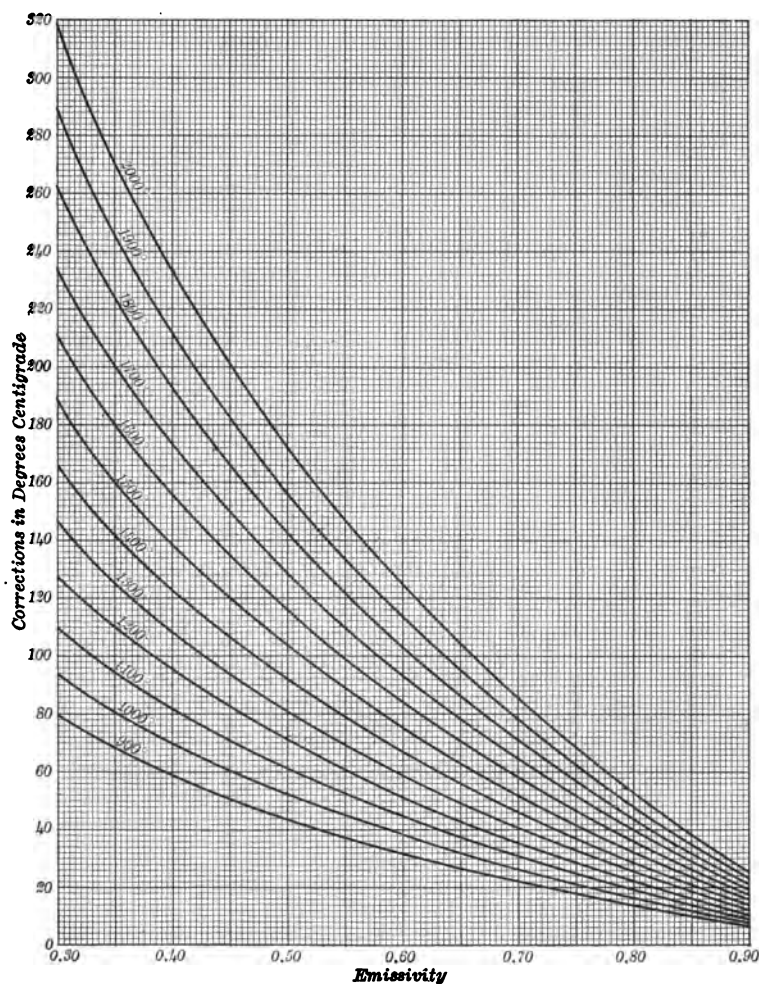

FIG. 53.

It is found that absorptive power varies considerably with the wave-length, but only slightly with temperature.   Consequently, knowing the absorptive power of a given substance for radiance

of a particular wave-length, together with the black-body temperature deduced from a determination of the rate of emission by the body of radiance of the same wave-length, we can compute the thermodynamic temperature of the body.

The wave-length of light usually employed in optical pyrometers is $\lambda = 0.65 \mu$. Using (44), the corrections to be added to readings of optical pyrometers using light of wave-length $\lambda = 0.65 \mu$, for a series of values of emissivity, have been computed * and the results here plotted in the curves of Fig. 53. Knowing the value of emissivity of the substance, the true or thermodynamic temperature, corresponding to any apparent or black-body temperature can be found from these curves without further computation. For example, liquid or incandescent solid iron and steel free from oxide has an emissivity of from 0.37 to 0.40. So that, assuming the latter value, a stream of iron at an apparent temperature of 1400° C. would have a true or thermodynamic temperature of 1523° C. Again since solid iron oxide has an emissivity of 0.92 the curves show that the true temperature of an ingot is practically the same as the apparent temperature obtained by an optical or radiation pyrometer.

Liquid iron oxide has an emissivity of 0.53; liquid slag, from 0.55 to 0.75, depending upon the composition, — "dark" slag being about 0.65. The emissivity of nickel is about that of iron. That of liquid copper 0.15 and of solid copper 0.11.

42. The Equality of Brightness Method of Measuring Temperatures. — The brightness of a luminous source is measured by the rate of emission of luminous radiance per unit area, and depends upon the temperature. When not above 3000° C., Wien's Distribution Law (39) expresses with considerable accuracy the relation between the black-body temperature of a source and the rate with which it emits luminous radiance for any specified wave-length. Hence, from a comparison of the brightness for any particular wave-length of two bodies, one can determine the ratio of the black-body temperatures of the given bodies. The method of determining temperatures from a comparison of

* Burgess — Technologic Papers of the Bureau of Standards, No. 91.

the brightness or the color of bodies is called Optical Pyrometry. An instrument that compares, for a particular color, the brightness of a hot body with the brightness of a standard lamp, and which is calibrated so as to indicate temperatures, is called an Equality of Brightness Optical Pyrometer.

If an image is formed of a luminous source, the quantity of energy of any particular wave-length in unit area of the image is a constant fraction of the energy of the same wave-length emitted during the same time from unit area of the source, if the distance from the source to the objective of the pyrometer be constant. When either a lens or a mirror is employed, the brightness of the image is independent of the distance of the lens or mirror from the source so long as the lens or mirror subtends the same solid angle at a point of the image. Whence, the ratio of the luminous energy per unit area of two sources can be obtained from a comparison of the brightness of the images of the sources.
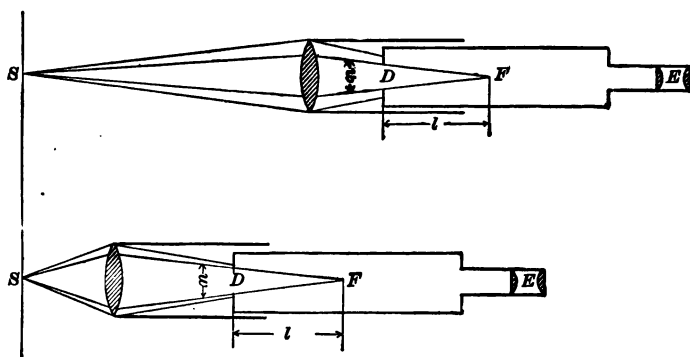

FIG. 54.

It will now be shown that the constancy of the angular aperture of a lens or mirror can be maintained by the use of a diaphragm having an opening of fixed area, at a fixed distance from the image. In Fig. 54, the image of the point S is formed at F, and is observed by means of the eyepiece E. In an ordinary telescope the distance of the image from the eyepiece changes

when the distance of the object changes, and the eyepiece must be moved forward or back correspondingly. Instead of this procedure, the eyepiece might be fixed, and the image maintained in the proper position relative to the eyepiece by moving the objective. If, in addition, there be a diaphragm D, with an opening of constant area A, at a fixed distance l, from the image, then whatever may be the distance from the object to the telescope, the solid angle subtended at the image by the objective will be $\dfrac{A}{l^2}$, which is a constant quantity henceforth to be represented by the symbol ω.

It is essential that an optical pyrometer should have:

(a) an invariable standard light source;

(b) an appliance for producing nearly monochromatic light;

(c) a sensitive photometric screen;

(d) a method for varying continuously and by a known amount the brightness of either one source or its image.

The luminous source used as a standard of comparison must be invariable in color and brightness. Incandescent electric lamps, and the flames of amyl acetate, gasoline, kerosene, and acetylene are employed as standard light sources.

Monochromatic light is best produced by means of a prism. Usually, however, colored glasses are used that give light which is nearly monochromatic. Since the absorptive power of colored glass is different for light of different wave-lengths, if there is any lack of monochromatism in the colored glasses, Wien's Distribution Law will not apply. If the colored glass transmits two bands or one wide band, the value of the absorption factor will be different at different temperatures.

Optical pyrometers, like total radiation pyrometers, compare black-body temperatures. In case two luminous sources radiate under black-body conditions, the ratio of their black-body temperatures equals the ratio of their thermodynamic temperatures. If the temperature of a "black-body" has been adjusted till the standard lamp of an optical pyrometer and the "black-body" have the same brightness for light of a particular wave-length,

and then the optical pyrometer is sighted on another body radiating under black-body conditions, the ratio of the thermodynamic temperatures of the "black-body" and the body under investigation can be obtained. If, in addition, the thermodynamic temperature of the "black-body" is known, then the thermodynamic temperature of the other black-body can be computed. Wherever possible bodies are observed when radiating under black-body conditions. The thermodynamic temperature of a steel ingot can be obtained directly from an observation of its brightness while it is in the soaking pit. On removal from the uniformly heated enclosure, the ingot will no longer radiate as a black-body and an observation of its brightness will give not thermodynamic temperature, but black-body temperature. If, however, its black-body temperature together with the absorptive power of its surface be known, the thermodynamic temperature can be computed from (44).

43. The General Optical Pyrometer Equation. — Representing by I_λ the rate with which radiance of wave-length λ leaves unit area of a hot source, and by J_λ the rate with which this radiance is incident on unit area of the image,

$$I_\lambda = z J_\lambda, \tag{45}$$

where z is a constant of proportionality.

Frequently the brightness of the image of either the source or the comparison lamp is too intense. In this event, one or more absorptive glasses can be used to diminish the intensity of the transmitted light. Let J_λ' be the rate with which energy of wave-length λ is incident on unit area of the image when an absorptive glass is used. Then we write:

$$J_\lambda = R_1 J_\lambda', \tag{46}$$

where R_1 is called the Absorptive Factor of the glass plate.

If a second piece of absorptive glass having an absorptive factor R_2 be added to the first plate, then

$$J_\lambda = R_2 (R_1 J_\lambda'),$$

and if several absorptive glasses are added:

$$J_\lambda = (R_1 R_2 R_3 \cdot \cdot \cdot) J_\lambda'. \tag{47}$$

Substituting this value in (45),

$$I_\lambda = z \, (R_1 R_2 R_3 \cdot \cdot \cdot) \, J_\lambda'. \qquad \cdot \qquad (48)$$

On substituting this value in Wien's Distribution Law (39), we have

$$\log I_\lambda \left[= C_1 - \frac{C_2}{K_\lambda} \right] = \log z + (\log R_1 + \log R_2 + \log R_3 + \cdot \cdot \cdot) + \log J_\lambda',$$

whence the black-body temperature

$$K_\lambda = \frac{C_2}{C_1 - \log z - (\log R_1 + \log R_2 + \log R_3 + \cdot \cdot \cdot) - \log J_\lambda'},$$

or, representing the constant quantity $(C_1 - \log z)$ by the symbol C_3 we obtain the general equation of optical pryometry,

$$K_\lambda = \frac{C_2}{C_3 - (\log R_1 + \log R_2 + \log R_3 + \cdot \cdot \cdot) - \log J_\lambda'}. \qquad (49)$$

· In case the image of the hot source is less bright than that of the comparison lamp, absorptive glasses can be placed in the path of light from the comparison lamp. In this case, the term within the parenthesis is positive.

The value of C_2 is given in (40). By methods to be hereafter described, the values of the other quantities in the right-hand member can be experimentally determined by means of the various optical pyrometers.

It should be noted that the K_λ in (49) represents temperature according to the black-body scale. If the emitting surface radiates as a black-body then the number which represents the temperatures according to the black-body seale equals that which represents the temperature according to the thermodynamic scale, that is, the symbol K_λ can be replaced by T. Also, if the emitting surface radiates as a black-body, the temperature obtained from (49) will be the same whatever be the wave-length of the light used in the measurement.

An inspection of the Table of Absorptive Powers, also shows that the absorptive powers of nonblack-bodies is different for radiance of different wave-lengths. From this it follows that

the monochromatic black-body temperature determined by means of radiance of one wave-length is not the same as that at a different wave-length. From (49) the same conclusion is evident; — that is, if the emitting surface does not radiate as a black-body, different values of K_λ will be obtained according to the wave-length of light used in the measurement. For this reason, in the case of nonblack-bodies, it is necessary to know the wave-length of the light employed in the measurement. Light of any conveniently obtained wave-length may be employed. But since when the temperature of a body is raised till the body becomes incandescent, red is the first color that appears, it follows that by using red light lower temperatures can be compared than by using light of any other color. There is a brand of glass that absorbs almost completely light of all wave-lengths except $\lambda = 0.65\ \mu$. This glass is now commonly used in optical pyrometry as a light filter. For this reason it is customary to use light of this wave-length in optical pyrometry even though a prism is used instead of colored glass to produce the monochromatic light.

Since the energy in the infra red part of the spectrum greatly exceeds that in the visible part, and since the absorptive power (and emissive power) of nonblack-bodies is less for the infra red than for the visible radiance, it follows that the rate of emission of visible radiance from nonblack-bodies is more nearly equal to the rate of emission of visible radiance from a black-body than is the rate of emission of the total radiance of nonblack-bodies equal to the rate of emission of total radiance from a black-body. Consequently an optical pyrometer calibrated against a black-body will give readings of the temperature of a nonblack-body that are nearer thermodynamic temperatures than will a radiation pyrometer.

The optical pyrometers now in use are essentially photometers for comparing the brightness of a spot of light from the hot source whose temperature is sought with that of a spot of light from a comparison lamp. The differences between the various types of optical pyrometers consist in the different types of comparison

lamp and in the methods of bringing to a photometric balance the light from the two sources.

44. The Color Identity Method of Measuring Temperature. — The radiating power of a body is directly proportional to its absorbing power. A body of perfect absorbing power for radiance of all frequencies is said to be black. A body that has an absorbing power less than unity, but which is the same for all frequencies is said to be gray. The color of a body depends only upon the relative amounts of light of the various frequencies radiated: the brightness depends upon the absolute amounts. The brightness of gray bodies is less than that of black-bodies at the same thermodynamic temperature, but the color of the light emitted by all black and all gray bodies at the same thermodynamic temperatures is the same. The fact that black and gray bodies at the same thermodynamic temperature are of the same color is the basis of a system of pyrometry called the Color Identity Method of Measuring Temperatures.

The determination of the temperature of a given body by this method consists in varying the temperature of a calibrated black or gray body till it has the same color as the given body. The temperature of the standard body is then that of the body under test. The standard of comparison is a "black-body" whose thermodynamic temperature is under control and that can be obtained by means of a calibrated thermoelectric pyrometer. A secondary standard of greater convenience in ordinary measurements is a carbon filament incandescent lamp for which the thermodynamic temperatures at various currents have been previously determined by matching the color against that of a "black-body."

45. Le Chatelier's Optical Pyrometer. — The first successful instrument for determining the temperature of a luminous source from a photometric comparison with a standard lamp consists of a telescope furnished with a side branch in which the standard lamp is placed. When in use, light from the body whose temperature is to be determined, and light from the standard lamp, form images side by side, in the focal plane of the eyepiece.

These images are brought to equality of brightness by means of an iris diaphragm in front of the objective. Approximate monochromatic light is produced by colored glasses. By means of the general optical pyrometer equation, the indications of this instrument can be transformed into black-body temperatures.

When directed toward a luminous object, light traverses the iris diaphragm, D, Fig. 55, and the objective O. The part of the beam that grazes the edges of the mirror M forms an image of the source in the focal plane of the eyepiece E. Light from
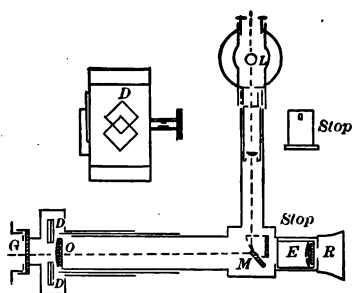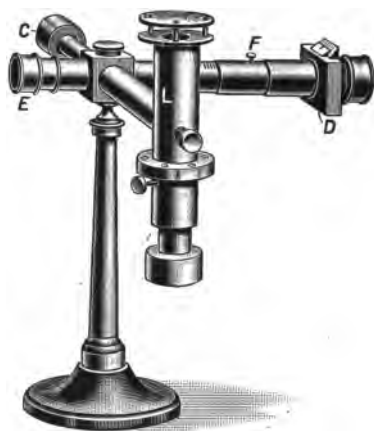

FIG. 55.   FIG. 56.

the comparison lamp L forms an image of the standard flame in the focal plane of the eyepiece, and by means of the mirror M is reflected into the eyepiece E. These two images, side by side, and separated only by a sharp line, are observed by means of the eyepiece E provided with a red filter R for rendering of approximately the same wave-length the light that enters the eye from the two images. The brightness of the image of the source is brought to equality with that of the image of the comparison flame by means of the iris diaphragm D. In case the source under investigation is very intense, the brightness of the image of the source is reduced by means of absorptive glasses G. In case the source under investigation is less bright than

the standard flame, an absorptive glass is placed in the path of the light from the standard flame instead of in the path of the light from the source. By the use of one or more absorptive glasses, the same instrument may be used for a wide range of temperature measurements.

46. The Féry Absorption Pyrometer. — This instrument, Figs. 57 and 58, includes a pair of wedges of absorptive glass ww', an objective O, a diaphragm of fixed aperture D, a Lummer-Brodhun prism xy, a comparison lamp L, objective O', totally reflecting prism P, ocular E and red filter glass R.
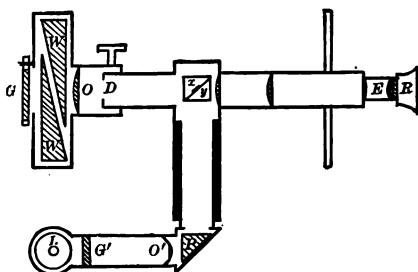
FIG. 57.   FIG. 58.

The Lummer-Brodhun prism consists of two right-angled prisms. The hypothenuse face of y is completely polished, while that of x has an unpolished round central spot. Light from the left incident upon the central portion of the hypothenuse faces will not be transmitted, whereas light incident outside of this spot will be transmitted to the ocular. Light from the comparison lamp incident upon the central spot of the hypothenuse faces will be totally reflected into the ocular, whereas that incident outside of this spot will be transmitted to one side of the instrument.

On looking through the ocular focalized on the center of the hypotheneuse faces, one sees a central round patch of light from the comparison lamp, surrounded by a ring of light from the source under investigation. If the brightness of the source is not much greater than that of the standard, the two images can be brought to equality of brightness by sliding the absorbing wedges. A scale attached to the wedges indicates the thickness of absorptive glass traversed by light from the source. After the instrument has been calibrated, the divisions on this scale will indicate black-body temperatures. The range of the Féry Optical Pyrometer may be extended by the use of absorptive glasses G and G', as in the case of the Le Chatelier instrument.

The diaphragm D ensures a fixed angular aperture so that no correction need be made for lack of focus, or for varying distance from the source.
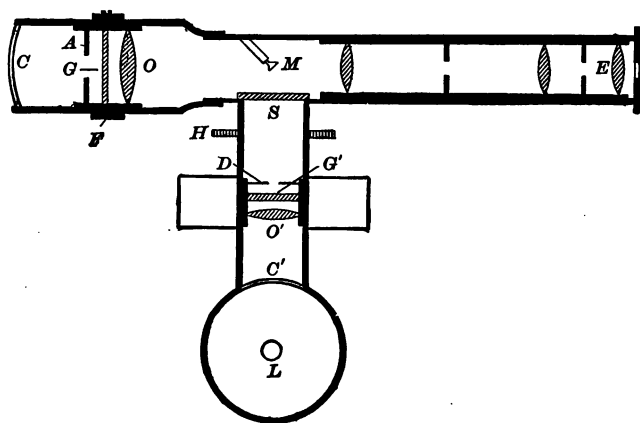
FIG. 59.

47. The Shore Pyroscope. — Various modifications of the Le Chatelier pyrometer have been devised by Shore, Féry, and others. In the Shore Pyroscope, Figs. 59 and 60, the brightness of the image of the source under investigation is maintained less than that of the comparison flame by means of a diaphragm A of fixed aperture placed in front of the objective. Light from the source, after traversing the diaphragm of fixed aperture A, the red

filter G, and the objective O, forms an image in the focal plane of the eyepiece. Light from the comparison flame L, after traversing the objective O', a red filter G', iris diaphragm D, and ground glass diffusing screen S, is reflected by the tiny mirror M and forms an image in the focal plane of the eyepiece. The objectives are protected by the cover glasses C and C'.

On looking through the eyepiece, one sees the image of an element of the comparison flame in the center of the image of the source whose temperature is sought. The brightness of the image of the comparison flame is reduced to that of the source by means of the iris diaphragm operated by the milled head H. The jaws of the iris diaphragm D have such a form that equal spaces on the divided circle attached to them represent equal differences on the blackbody temperature scale.

FIG. 60.

The Shore Pyroscope is focalized by moving the objective by means of the knurled head F. Though there is no diaphragm between the objective and the image, this arrangement makes the angular aperture of the objective so nearly constant that there is no serious error introduced by changing the distance between the instrument and the body whose temperature is sought.

48. The Morse Thermogauge or Holborn-Kurlbaum Optical Pyrometer. — This instrument differs from those of the Le Chatelier type in that instead of projecting the image of the comparison source on the focal plane of the objective, the comparison source itself is placed there, and its brightness is adjusted to equality with the brightness of the image of the source whose temperature is sought.

The comparison source L, Fig. 61, is a 4-volt electric incandescent lamp placed in the focal plane of the objective O. The

current is adjusted by means of a rheostat in circuit with the lamp. In using the instrument, the telescope is directed to the source whose temperature is sought; the objective O is moved back and forth till the image of the source is in the plane of the filament of the electric lamp, and the current is adjusted till the tip of the filament just disappears against the bright background. When this occurs, the

FIG. 61.

temperature of the filament equals the apparent black-body temperature of the image. Thus, the value of the current when the tip of the filament is invisible is a measure of the black-body temperature of the source.
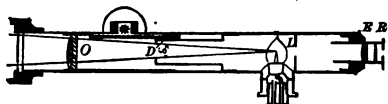
The light that reaches the eye is rendered approximately monochromatic by a red glass R. When bodies at very high temperature are observed, the light is so dazzling that the brightness is reduced by one or more absorptive glasses placed in front of the objective. Excessive heating of the filament of the comparison lamp is thereby also obviated.

The diaphragm D at a fixed distance from the image of the source renders the angular aperture of the objective constant. Thus the brightness of the image of the source is independent of the distance of the telescope from the source.

The original Morse Thermogauge was without diaphragm or lenses. The present form of the instrument is provided with these important improvements due to Holborn and Kurlbaum.

49. The Wanner Optical Pyrometer. — In the Wanner Pyrometer, light from the source whose temperature is sought, and light from a comparison source, are drawn out into two spectra. From these two spectra, two narrow stripes of the same width and the same wave-length are isolated and the intensities of these stripes are compared by means of a polarizing device. Light from the hot source traverses the cover glass C and the slit S_1, Fig. 62, while light from the comparison lamp L, after traversing a diffusing glass, is reflected by the mirror M into the slit S_2. Each beam is rendered parallel by the objective O, and

each is spread out into a spectrum by the direct vision prism V. The Rochon double image prism R separates each beam into two beams, polarized in planes at right angles to one another. Each of these beams falling on both faces of the wide angled
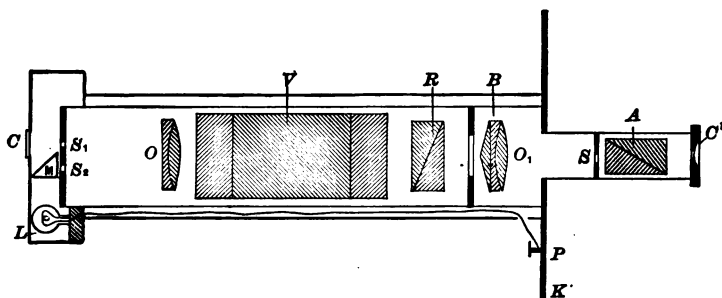

Fig. 62.

prism B is again divided into two. The Wanner Optical Pyrometer is essentially a double-slit direct-vision spectroscope to which has been added the polarizing prism R, analyzing prism A, and wide angled prism B cemented to the ocular O_1.

If the polarizer R and wide angled prism B were not present there would be formed in the plane of the diaphragm S, a spectrum due to light that had traversed the slits S_1 and S_2. In Fig. 63, these spectra are represented by "1" and "2" respectively. With the Rochon polarizing prism R in place, each of these spectra is divided into two, — one consisting of plane polarized light

Fig. 63.

with the vibrations vertical, and the other with the vibrations horizontal. In the diagram, these spectra are represented by the symbols 1_v, 1_h, 2_v, 2_h. With the wide angled prism B in place, all four beams impinge on both faces of the prism. The parts of the four beams that strike the upper face of the double image prism will be refracted downward. On emergence these parts are distinguished in the diagram by "primes." The parts of the beam that strike the lower face will be bent

upward. On emergence these parts are distinguished in the diagram by "seconds."

The four beams that strike the upper half of the wide angled prism emerge side by side and are focalized by the lens O_1 in the plane of the diaphragm S. In the same manner, the four beams that strike the lower half of the wide angled prism, emerge side by side and are focalized by the lens O_1 in the plane of the diaphragm S. The wide angled prism B is so tilted that these two rows of spectra will not be superposed but will form two bands side by side and in the same plane. In Fig 63, the two rows of spectra $(2_h', 2_v', 1_h', 1_v')$ and $(2_h'', 2_v'', 1_v'', 1_h'')$ should not be in different planes as there represented, but should be in one plane perpendicular to the page. In the eyepiece diaphragm S, there is a slit parallel to the slits S_1 and S_2, which cuts off all the light except a narrow stripe out of the red from one of the ordinary beams that originated at the hot source, and a similar stripe of the same wave-length from one of the extraordinary beams that originated at the comparison source.

The field of view of the instrument is thus divided into two halves by a sharp division line. One half of the field is illumined by plane polarized light from the hot source, while the other half is illumined by light coming from the comparison lamp polarized in the plane at right angles to the first. By interposing 'a Nicol prism A, Fig. 62, between the diaphragm and the eye, the two halves may be brought to equal brightness.

The comparison lamp L is a 6-volt incandescent lamp "aged" by being operated for several hours at an excessive voltage. By means of a rheostat and ammeter, the current in the comparison lamp can be adjusted to give constant brightness.

It should be added that in some Wanner Optical Pyrometers, a piece of red glass is used to produce approximately monochromatic light instead of the dispersing prism described above.

50. The Wide Filament Pyrometer Comparison Lamp. — Optical as well as radiation pyrometers can be calibrated by means of a "black-body" operated at a series of known temperatures. Electrically heated tube furnaces, however, are expensive

to maintain and they lack portability and ease of operation. These objections do not apply to a wide filament incandescent lamp capable of being operated at high temperatures. By means of a calibrated optical pyrometer and ammeter, the black-body temperature of the wide filament when traversed by various known currents can be obtained. Such a calibrated pyrometer comparison lamp can be used instead of a "black-body" for the calibration of optical pyrometers as seen in Fig. 69.

Exp. 7. Calibration of a Le Chatelier Optical Pyrometer

THEORY OF THE EXPERIMENT. — Read Arts. 40, 42, 43, 45. When an electrically heated tube furnace provided with a calibrated thermocouple is at hand, any pyrometer can be calibrated directly throughout the range of the furnace. Often, however, such a step-by-step method is inconvenient or impossible. In the following paragraphs it will be shown how a calibration curve of the Le Chatelier Optical Pyrometer can be constructed from a single temperature observation. The object of this experiment is to construct the calibration curve of a Le Chatelier Optical Pyrometer by the step-by-step method, and also by means of a single temperature observation and an equation now to be derived.

When the objective lens O, Fig. 55, is directed toward the body whose temperature is sought, and the comparison lamp L is maintained at constant brightness, a photometric balance can be obtained by varying the brightness of the image of the hot source by means of the iris diaphragm D. The length d, of one side of the square aperture of the dia-

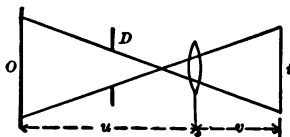

FIG. 64.

phragm is observed on the scales attached to the two jaws.

Let O, Fig. 64, represent a luminous object of effective area A_o; i, its image of area A_i; and D a diaphragm containing a square aperture having a side of length d. If the rate of radiation per unit area of the source be represented by I_λ, and

the rate with which radiance of wave-length λ is incident on the image when there is no absorptive glass be represented by J_λ,

$$J_\lambda \propto \frac{I_\lambda A_o}{u^2}.$$

Also, $$J_\lambda \propto d^2,$$

where d is the length of one side of the aperture.

Then $$J_\lambda = C' \frac{I_\lambda A_o}{u^2} d^2.$$

That is, $$I_\lambda = C \frac{J_\lambda u^2}{A_o d^2}. \qquad (50)$$

But from a property of lenses,

$$\frac{A_o}{A_i} = \frac{u^2}{v^2} \quad \text{or} \quad A_o = A_i \frac{u^2}{v^2}.$$

On substituting this value in (50)

$$I_\lambda = \frac{C v^2 J_\lambda}{A_i d^2}. \qquad (51)$$

If absorptive glasses having absorptive factors, R_1, R_2, and R_3, etc., be interposed between the objective and the image, then the rate with which energy of wave-length λ is incident on unit area of the image has a value J_λ' given by the relation (47)

$$J_\lambda = (R_1 R_2 R_3 \ . \ . \ .) J_\lambda'.$$

And the preceding equation becomes

$$I_\lambda = \frac{C v^2 J_\lambda'}{A_i d^2} (R_1 R_2 R_3 \ . \ . \ .). \qquad (52)$$

If in the experiment, the brightness of the image be kept constant by regulating the diaphragm, then the quantity $\dfrac{J_\lambda'}{A_i}$ is constant. If, in addition, the instrument be kept at a fixed distance from the source, v^2 is constant. Then, under these experimental conditions, the above equation becomes

$$I_\lambda = C'' \frac{(R_1 R_2 R_3 \ . \ . \ .)}{d^2}.$$

Substituting this value in Wien's Distribution Law (39), we have,

$$\log I_\lambda \left[= C_1 - \frac{C_2}{K_\lambda} \right] = \log C'' + \log R_1 + \log R_2 + \log R_3 - 2 \log d,$$

whence,

$$K_\lambda = \frac{C_2}{C_4 - (\log R_1 + \log R_2 + \log R_3 + \cdots) + 2 \log d}, \quad (53)$$

where C_4 represents the constant quantity $(C_1 - \log C'')$.

Before (53) can be used to measure temperatures, the constants C_2 and C_4 must be determined. And if absorptive glasses are used, their absorptive factors, R_1, R_2, R_3, etc., must also be known.

MANIPULATION. — Fill the comparison lamp with gasoline, light the wick and adjust the position of the flame till the field of view in the eyepiece due to the comparison flame is uniformly bright. Focalize the telescope of the instrument on the red hot carbon block in the electrically heated "black-body" which supports the hot junction of a calibrated thermocouple. Note
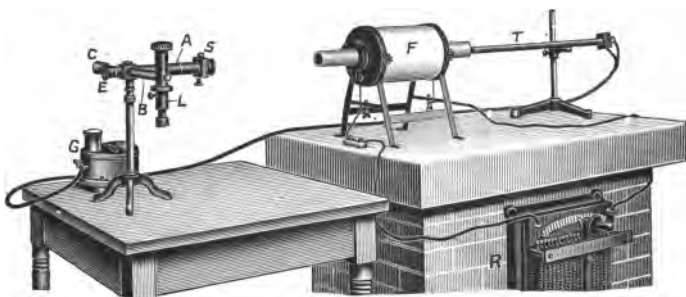

FIG. 65.

the reading on the scale engraved on the telescope tube when the instrument is in focus. The calibration now to be obtained will apply only when the telescope is of this particular length.

By means of an ice bath, not shown in Fig. 65, keep the cold junction of the thermoelectric pyrometer at a constant temperature.

At a known temperature, as low as it is possible to make settings, take a reading of the aperture without the absorptive glass and also with the absorptive glass. Increase the temperature by 25° intervals for four settings and take a similar pair of readings at each temperature. Now increase the temperature by 50° intervals as far as desired, and take similar pairs of readings. From these observations construct on one pair of coordinate axes, the step-by-step calibration curve of the instrument without absorptive glass, and also the one with the absorptive glass. Lay off temperatures along the axis of abscissas, and diaphragm apertures along the axis of ordinates.

The calibration curve is now to be constructed by means of the law of the instrument expressed in (53). The constants C_2 and C_4 can be obtained if we know the wave-length of the light transmitted by the monochromatic filter glass R, Fig. 55, together with the length of one side of the iris diaphragm D when the standard flame balances photometrically the light from a body of known temperature. If the wave-length of the light transmitted by the filter glass is not known, the constants C_2 and C_4 can be determined from readings obtained from a body at two known temperatures. The former method is susceptible of greater precision and will be first considered.

To obtain C_2, the wave-length of the light transmitted by the filter glass is most easily obtained by means of a direct vision spectroscope with scale of wave-lengths. Then, (40),

$$C_2 = \frac{6297}{\lambda}.$$

Knowing C_2, together with the value of d, corresponding to one known temperature, the value of C_4 can be determined. For this purpose, note the coordinates d and K_λ of any convenient point of the previously obtained calibration curve. If no absorptive glass be used, $R_1 = R_2 = R_3 = 0$. In this case, the values of C_2, K_λ and d, now at hand, substituted in (53) will give us the value of C_4. The value of C_4 thus obtained will hold so long as the conditions involved in (53) are fulfilled.

If an absorptive glass be used, the absorptive factor, R_1 can be found as follows: Direct the instrument toward a frosted globe incandescent lamp or other uniformly bright constant light source; bring the two halves of the field of view to equal brightness and note the length d_1 of one side of the aperture in the diaphragm. Then insert the absorptive glass; obtain a photometric balance, and note the new length d_2 of the aperture.

When no absorptive glass was used, we have, (51),

$$I_\lambda = \frac{Cv^2 J_\lambda}{A_i d_1^2}; \tag{54}$$

and when one absorptive glass was used having an absorptive factor R_1, we have, (52),

$$I_\lambda = \frac{Cv^2 J_\lambda' R_1}{A_i d_2^2}. \tag{55}$$

During these two measurements the intensity of the source I_λ is constant. And since the brightness of the image, in both cases, is that of the comparison flame, $J_\lambda = J_\lambda'$. Whence, equating the right-hand members of (54) and (55), we obtain

$$R_1 = \left(\frac{d_2}{d_1}\right)^2. \tag{56}$$

If several absorptive glasses are used, the absorptive factor of each may be separately determined as above.

Now that all the constants of (53) have been determined, values of K_λ corresponding to a series of values of d can be computed. From such a table of values of K_λ and d, construct a curve coordinating black-body temperatures and pyrometer readings.

On the sheet with the step-by-step calibration curve, lay off temperatures along axis of abscissas, and diaphragm apertures along axis of ordinates. This curve should coincide with the one previously obtained.

Sometimes no instrument is at hand for the determination of the wave-length of the light used. If two known temperatures are available, the constants C_2 and C_4 can be determined with a fair

degree of accuracy even though λ is unknown. Thus, suppose that at temperatures K_λ' and K_λ'', when no absorptive device is used, the scale readings are d_1 and d_2, respectively.

Then from (53)

$$K_\lambda' = \frac{C_2}{C_4 + 2 \log d_1}, \tag{57}$$

and

$$K_\lambda'' = \frac{C_2}{C_4 + 2 \log d_2}. \tag{58}$$

Whence, solving for C_4 by eliminating C_2,

$$C_4 = \frac{2(K_\lambda'' \log d_2 - K_\lambda' \log d_1)}{K_\lambda' - K_\lambda''}. \tag{59}$$

On substituting the numerical values of C_2 and C_4, together with the values of the absorptive factors of any glasses that may be used, a series of definite values of d can be computed that correspond to any assigned values of K_λ. From a series of corresponding values of d and K_λ thus obtained, a calibration curve can be drawn.

In either of the manners above described a calibration curve is to be constructed, when the instrument is provided with an absorptive glass, and another when it is not.

It should be noted that the Le Chatelier Optical Pyrometer is focalized by moving the objective instead of by moving the eyepiece. But as there is no diaphragm between the objective and the image, the angular aperture of the objective is not quite constant when the distance from the instrument to the object is changed. The error thereby introduced into temperature determinations is, however, always small. For example, if the distance from the telescope to the object be changed by 25 per cent, then even without refocalizing, the error would be only about 5 per cent.

The commercial form of Le Chatelier's instrument cannot be focalized on an object nearer than about three feet. When the instrument is used at a minimum distance, the object must be not less than 5 mm. on a side.

Exp. 8. Calibration of a Wanner Optical Pyrometer

THEORY OF THE EXPERIMENT. — Read Arts. 40, 42, 43, and 49.
A calibration curve can be constructed from a series of obser-
vations of scale readings corresponding to a large number of
known temperatures. Oftentimes, however, it is impossible to
produce such a series of known temperatures throughout the
range for which it is desired to use the instrument. In the fol-
lowing paragraphs it will be proved that a calibration curve can
be constructed from the discussion of data obtained from the
observation of a black-body at but one known temperature.
The object of this experiment is to construct a curve coordinating
black-body temperatures of a luminous object with the scale
readings of a Wanner Optical Pyrometer, first, by the step-by-
step method, and second by means of Wien's Distribution Law
and a reading made on a black-body at known temperature.

It will first be shown that when the two halves of the field of
view are of equal brightness, the angle between the plane of
polarization of the analyzer A, Fig. 62, and the plane of polari-
zation of the light in the half of the field of view due to the source,
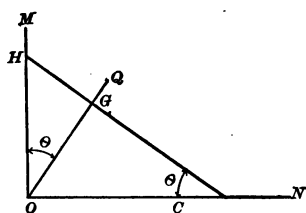is a measure of the ratio of the brightness of the two sources.

FIG. 66.

It will then be shown that by intro-
ducing this result into the general
optical pyrometer equation, the ratio
of the black-body temperatures of any
bodies can be determined.

In Fig. 66, let OM be the plane of
polarization of light in the half of the
field of view coming from the hot
source and let ON be the plane of polarization of the light in
the other half coming from the comparison source. Let OH
and OC represent the amplitudes of vibration of the light con-
stituting these two halves of the field of view. Let OQ be the
plane of transmission of the Nicol prism when the two halves of
the field of view are of equal brightness. This equality requires
that the angle θ must be such that the projection of OC on OQ

equals the projection of OH on OQ. That is, OQ is perpendicular to HC. It follows that

$$OG = OH \cos \theta = OC \sin \theta.$$

That is, the amplitudes of vibration of the light in the field of view of the instrument coming from the two sources are in the ratio

$$\frac{OH}{OC} = \tan \theta.$$

Representing the brightness of the field of view due to the hot source by J_λ' and the brightness of the field of view due to the comparison source by J_λ'', and remembering that brightness varies directly with the square of the amplitude of vibration, we have

$$\frac{J_\lambda'}{J_\lambda''} \left[= \frac{(OH)^2}{(OC)^2} \right] = \tan^2 \theta. \tag{60}$$

Since at 45° the value of the tangent of an angle changes least with a given change of angle, the indications of a Wanner pyrometer are most sensitive when the angle between the polarizer and analyzer is 45°. Or expressed in another way — at around 45° small changes of intensity will necessitate large movements of the index hand, while in the neighborhood of 0° or 90° smaller movements of the index hand would be required. When the temperature of the hot source is much higher than that of the comparison source, the angle θ will be much greater than 45° and the readings will be lacking in sensitiveness. To obviate this, an absorptive glass may be placed in the path of the light from the hot source.

Since the Wanner Optical Pyrometer compares the luminous intensity of radiance of the same wave-length from two sources, the ratio of the black-body temperatures of the two sources can be obtained by means of Wien's Distribution Law. Let monochromatic light from the hot source be photometrically balanced against light of the same wave-length. Substituting in the general equation of optical pyrometry (49) the value of J_λ' given in (60) we obtain for the Wanner Optical Pyrometer,

$$K_\lambda = \frac{C_2}{C_3 - (\log R_1 + \log R_2 + \cdots) - \log J_\lambda'' - \log \tan^2 \theta}.$$

When the brightness of the comparison lamp is constant, the quantity $(C_3 - \log J_\lambda'')$ is constant and may be represented by the symbol C_5. Whence,

$$K_\lambda = \frac{C_2}{C_5 - (\log R_1 + \log R_2 + \cdots) - \log \tan^2 \theta}. \qquad (61)$$

If the absorptive glasses are not used, the quantity within the parenthesis becomes zero. Assuming this arrangement, the comparison lamp at constant brightness, and the constants λ, C_2, and C_5 known, a series of values of θ can be substituted in this equation, and the corresponding values of K_λ computed. These values can be conveniently coordinated by a curve. If now the pyrometer be directed toward an incandescent body of known black-body temperature K_λ, the analyzer set at the angle θ which the previously constructed curve shows corresponds to this value of K_λ, and the current in the comparison lamp adjusted till the two halves of the field of view are equally bright, the pyrometer will be in adjustment with the previously constructed curve.

If, thereafter, the comparison lamp be maintained at its present brightness, the black-body temperature of any incandescent body can be obtained. The operation consists in directing the instrument toward the hot source, rotating the analyzer till a photometric balance is obtained, observing the angle θ, and looking up on the calibration curve or table the temperature that corresponds to the particular angle.

If the range of the instrument is to be increased by the use of absorptive glasses placed between the hot body and the pyrometer then in (61) the term within the parenthesis does not become zero. Consequently, in calculating the temperatures for various values of θ we shall have to know the numerical values of R_1, R_2, etc. From (46) we see that with a single absorptive glass of absorptive factor R_1,

$$R_1 = \frac{J_\lambda}{J_\lambda'}, \qquad (62)$$

where J_λ represents the brightness of the field of view due to the hot source when no absorptive glass is interposed, and J_λ' rep-

resents the brightness when an absorptive glass of absorptive factor R_1 is interposed.

If the brightness of the field of view due to the comparison lamp be denoted by J_λ'', then from (60)

$$J_\lambda = J_\lambda'' \tan^2 \theta,$$

and $$J_\lambda' = J_\lambda'' \tan^2 \theta'.$$

Whence (62), $$R_1\left[= \frac{J_\lambda}{J_\lambda'}\right] = \frac{\tan^2 \theta}{\tan^2 \theta'}. \tag{63}$$

This equation shows that to determine the absorptive factor R_1 of a piece of glass it is only necessary to direct the Wanner Optical Pyrometer toward any uniformly luminous source, rotate the Nicol until a photometric balance is obtained, read the angle θ; then after interposing the absorptive glass between the pyrometer and the luminous source, balance the fields again and read θ'. These values substituted in (63) give the numerical value of the absorptive factor.

MANIPULATION. — To find the temperature K_λ, by means of (61) it is necessary to experimentally determine the wave-length of light transmitted by the instrument, together with the absorptive factor of each absorptive glass used in front of the objective.

As the slit in the ocular of the pyrometer is fairly wide, the field of view is not strictly monochromatic, but is a more or less narrow band in the red portion of the spectrum formed by the prism. The wave-lengths of the light at the edges of the band must be found and their mean taken as the value of λ. The most convenient method of measuring the wave-lengths is by the use of the spectrometer provided with a scale of wave-lengths. Have the pyrometer directed toward the sun, an arc lamp or other intense light source, and place in front of the eyepiece a direct-reading spectrometer. On looking into the eyepiece of the spectrometer a bright band will be seen. On the scale of the spectrometer the wave-lengths of the edges can be read.

To determine the absorptive factor of an absorptive glass, direct the pyrometer toward a frosted globe incandescent lamp or other convenient nearly uniformly lighted surface, and set the

current in the comparison lamp at any convenient value which must be maintained constant while taking the following observations. Balance the photometric fields and read the angle. Place the plate of absorptive glass in front of the objective, again obtain a balance and read the angle. From the values of these two angles calculate R_1 from (63). .

With the already measured value of λ calculate C_2 from (40).

Since the indications of a Wanner pyrometer are most sensitive when the angle between the polarizer and analyzer is 45°, and since by properly adjusting the intensity of the comparison lamp the two fields can be balanced at 45° for a wide range of temperatures of the hot source, it will be convenient to adjust the comparison lamp till the reading is 45° for the particular temperature at which most precise readings are desired. Assuming some temperature K_λ, at which θ is to be 45° without absorptive glasses, and knowing the value of λ and of C_2, the value of C_5 can be computed from (61).

Substitute the values of C_2 and C_5, now determined, in (61), and compute the temperatures corresponding to various angles extending from 10° to 80° at intervals of 5° when no absorptive glasses are used.

Also compute the temperatures for the same angles when one absorptive glass of known absorptive factor is used.

The following concrete example will illustrate the method. Let it be required to construct a calibration curve for a Wanner Optical Pyrometer arranged to be most sensitive for a temperature of 900° C. It was found by measurement that the band transmitted by this particular instrument extends from $\lambda = 0.674\,\mu$ to $\lambda = 0.638\,\mu$. The means of these values gives $\lambda = 0.656\,\mu$.

From (40)

$$C_2 \left[= \frac{6297}{\lambda} \right] = \frac{6297}{0.656} = 9599.$$

Since we wish to make the most sensitive part of the scale at 900° C., then at 45° the value of $K\lambda$ is to be $900 + 273 = 1173$. From (61) we have, when no absorptive glasses are used:

$$1173 = \frac{9599}{C_5 - 0 - 0} .$$

Whence

$$C_5 = 8.183.$$

Knowing the values of C_2 and C_5 we can calculate the values of K_λ corresponding to various angles.

The data obtained for determining R_1 were as follows:

$$\theta = 63°,$$
$$\theta' = 58°.5.$$

Therefore (63), $\qquad R_1 = \dfrac{\tan^2 63°}{\tan^2 58°.5},$

$$\log R_1 = \log \tan^2 63° - \log \tan^2 58°.5$$
$$= 0.58566 - 0.42536$$
$$= 0.16.$$

We are now prepared to find the temperature that corresponds to any regular setting θ when no absorptive glass is used and also when one is used having the absorptive factor just determined.

From (61), with the absorptive glass, a setting of the analyzer at the angle $\theta = 20°$ corresponds to a black-body temperature

$$K_\lambda = \frac{9599}{8.18 - 0.16 - (-0.88)} = 1077° \text{ absolute} = 804° \text{ centigrade.}$$

In this manner make the necessary computations and construct a table for values of θ extending from 10° to 80° with 5° intervals as indicated below.

θ	Log $\tan^2 \theta$	Log $R_1 = 0$		Log $R_1 = 0.16$	
		K_λ abs.	K_λ cent.	K_λ'abs.	K_λ'cent.
10°					
15°					
20°	−0.88	1059°	786°	1077°	804°
25°					

With temperatures as abscissas and angles as ordinates, plot two curves on the same sheet coordinating θ with K_λ centigrade and θ with K_λ' centigrade. These curves are the calibration curves of the instrument with and without the particular absorptive glass plate used above.

To make the above calibration curves of use in measuring temperatures it is necessary that the current through the comparison lamp be set at a definite value which must be kept constant when the pyrometer is used thereafter.

To find the value of this current, heat the "black-body" up to a temperature well within the range of the instrument. Sight the pyrometer on the septum that supports the hot end of the thermoelectric couple and note the temperature by means of an indicator connected to the standard thermocouple in the furnace. From the calibration curve just obtained find the angle corresponding to the thermodynamic temperature of the furnace. Set the analyzer of the pyrometer at this angle, and regulate the current in the comparison lamp till the two halves of the field of view in the pyrometer eyepiece are equally bright. Note the value of the current now in the comparison lamp. When the pyrometer is used thereafter to determine temperatures, the current must be maintained at this value.

Fig. 67.

To verify the calibration curves plotted above, heat the "black-body" to several different temperatures and take the readings of the standard thermoelement simultaneously with the settings of the analyzer. Make each setting with and without the absorptive glass. On the sheet containing the calibration curves, plot the series of points obtained from the settings of the analyzer and the temperature observed with the thermo-element, when no absorptive glass was used, and another similar series curve when an absorptive glass was used.

Instead of reading angles and then finding the temperatures from a previously constructed calibration curve, it is common practice to divide the circular scale of the instrument so as to indicate black-body temperature directly. If the instrument

being calibrated is provided with both a scale in degrees and a scale in temperatures a Table of Corrections should be constructed.

Since the Wanner Pyrometer makes use of a polarizing device for the equalization of the brightness of two light beams, polarized light should not enter the instrument. Most incandescent surfaces emit partially polarized light, but the degree of polarization of the light emitted normal to surface is the minimum. Hence, the Wanner Pyrometer should be directed normally to the hot surface whose temperature is sought.

Since the images observed are of the slits of the instrument and not of the source sighted upon, no focusing is required for various distances from the object. Care must be exercised that the pyrometer is sufficiently near the object that the field of view due to the object shall be uniformly bright. To prevent the instrument being overheated, the model sold under the trade name "Scimatco" is enclosed in a double-walled metal case as illustrated in Figs. 62 and 67.

If after calibration, the comparison lamp should change in brightness, the calibration curve would no longer apply. But the constancy of the electric comparison lamp can be readily checked at any time by comparison with a flame of constant intensity. For example, at the time of calibration let the optical pyrometer be directed toward the flame of a standard amyl acetate pyrometer lamp, and the analyzing Nicol prism be turned till the two halves of the field of view in the eyepiece are equally bright. The present setting of the analyzer is called the Normal Point of the particular instrument. With the Nicol at the normal point, if at any subse-

Fig. 68.

quent time the instrument be directed toward the standard flame, the two halves of the field of view should be equally bright. If this is not the case, the current in the comparison lamp should be adjusted till equality of brightness is attained. After this
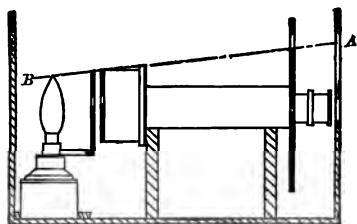
adjustment, the previously obtained calibration curve will apply to readings of the instrument.

In making the check, the pyrometer and the standard amyl acetate lamp are placed in the carrying case, at definite positions marked by the maker. The height of the flame is adjusted till the tip can just be seen when the line of sight AB is as indicated in Fig. 68.

Exp. 9. Calibration of a Holborn-Kurlbaum Optical Pyrometer

THEORY OF THE EXPERIMENT. — Read Arts. 40, 42, 43, and 48. The object of this experiment is to construct a calibration curve of a Holborn-Kurlbaum Optical Pyrometer, first, by the step-by-step method, then by means of the general optical pyrometer equation and three known temperatures.

The theory of the latter method will now be considered. It depends upon the fact that the relation between the current through a carbon filament and its black-body temperature varies with each filament, but in all cases is represented for a considerable range by a formula of the type,

$$i = a + bt + ct^2, \qquad (64)$$

where i represents the current (usually expressed in milliamperes), t represents the black-body temperature in centigrade degrees, and a, b, c are constants depending upon the filament. To determine these three constants the temperature must be known for three known values of the current. By means of this relation a calibration curve can be extended beyond the temperature range through which measurements have been made. We will now obtain the equation connecting the temperature K_λ, of a body that produces an image of certain brightness when no absorptive device is used, and the temperature K_λ' that the body would need to have in order that the image may be of the same brightness when an absorptive device is used.

Let I_λ be the rate of emission of energy of wave-length λ by the source whose absolute black-body temperature is K_λ.

Then by (39)

$$\log I_\lambda = C_1 - \frac{C_2}{K_\lambda}. \qquad (65)$$

If J_λ' be the rate at which energy emerges from the objective, then

$$I_\lambda = zJ_\lambda'. \qquad (66)$$

Now let an absorptive glass of absorptive factor R be placed in front of the objective and let the temperature of the source be raised until the rate at which energy emerges from the objective is the same as before. Then if K_λ' is the present temperature of the source, and I_λ' is the rate of emission of energy of wavelength λ from the source at this temperature,

$$\log I_\lambda' = C_1 - \frac{C_2}{K_\lambda'}, \qquad (67)$$

and

$$I_\lambda' = zRJ_\lambda'. \qquad (68)$$

Subtracting from each member of (67) the corresponding member of (65)

$$\log \left(\frac{I_\lambda'}{I_\lambda}\right) = C_2\left(\frac{1}{K_\lambda} - \frac{1}{K_\lambda'}\right). \qquad (69)$$

Substituting from (66) and (68) into (69)

$$\log \left(\frac{zRJ_\lambda'}{zJ_\lambda'}\right) = C_2\left(\frac{1}{K_\lambda} - \frac{1}{K_\lambda'}\right),$$

or,

$$\frac{\log R}{C_2} = \frac{1}{K_\lambda} - \frac{1}{K_\lambda'}. \qquad (70)$$

Setting $\dfrac{\log R}{C_2} = C_6$, we obtain

$$\frac{1}{K_\lambda'} = \frac{1}{K_\lambda} - C_6. \qquad (71)$$

This equation gives the relation between the black-body temperature K_λ of a source that produces an image of a certain brightness, and the black-body temperature K_λ' that the source would need to have in order that light from it after traversing an absorptive medium shall form an equally bright image. Equation (64) gives the relation between the current in the comparison

lamp and the black-body temperature of the filament. When the comparison lamp filament is of the same brightness as the image of the source, the temperature of the comparison lamp equals the apparent temperature of the image. Whence, if the filament has a constant radiating power, the same equation with different values for the constants will express the relation between the current in the comparison lamp and the black-body temperature of the sources sighted upon.

MANIPULATION. — Direct the Holborn-Kurlbaum Optical Pyrometer to the wide filament of a calibrated pyrometer lamp, Art. 50. Adjust the pyrometer till the top of the filament in the eyepiece is superposed on the image of the wide filament of the pyrometer lamp, and till there is no motion of one relative to the other when the eye is moved from one side to the other in front of the eyepiece.

With no absorptive glass between the wide filament pyrometer lamp and the objective of the optical pyrometer, first adjust the
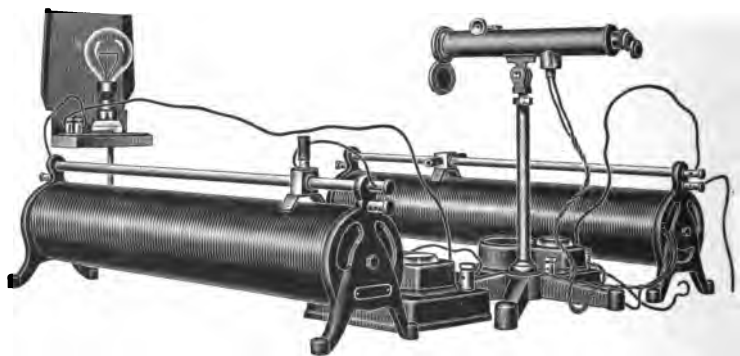

FIG. 69.

current in the wide filament pyrometer lamp till the filament is dull red. Then adjust the current in the comparison lamp in the eyepiece of the pyrometer till the tip of the filament disappears against the back-ground formed by the image of the wide filament of the pyrometer lamp. Note the current in the wide filament pyrometer lamp and the current in the comparison

lamp. Also, from the calibration curve of the wide filament pyrometer lamp, note the present black-body temperature of the filament. In the same manner, take simultaneous readings of the current in the comparison lamp and in the wide filament pyrometer lamp at intervals of about 100° C. throughout the range of the wide filament pyrometer lamp.

With these data plot as abscissas values of K_λ according to the centigrade scale, and as ordinates values of i expressed in milliamperes. This is the empirical calibration curve of the instrument, when no absorptive glass is used. The equation of this curve is of the form (64). From the coordinates of three points of the curve compute the constants a, b, and c. The definite equation obtained by substituting these values in (64) is the equation of the calibration curve when no absorptive glass is used. Only three known temperatures are required to construct this curve. Check this equation by computing values of i corresponding to a series of assigned values of K_λ, according to the centigrade scale, at 100° intervals from 600° C., to 1500° C. On the same sheet with the empirical calibration curve plot this computed calibration curve and compare the two curves.

The calibration curve of the instrument when an absorptive glass is used is now to be computed. Find the wave-length λ of the light transmitted by the instrument by means of a spectrometer provided with a scale of wave-lengths. Knowing λ, the constant C_2 as given by (40) is

$$C_2 = \frac{6297}{\lambda}.$$

The absorptive factor can be determined by means of a Wanner Pyrometer as described in exp. 8, or by means of any spectro-photometer. Knowing C_2 and R, the value of C_6 is determined by its value

$$C_6 = \frac{\log R}{C_2}.$$

With this value of C_6 find by means of (71) several values of the temperature K_λ' of the pyrometer lamp corresponding to

values of K_λ. Now express these values of K_λ' on the centigrade scale and plot them against the current i, corresponding to the above values of K_λ. This is the calibration curve of the instrument when the absorptive glass is used.

In determining temperatures by means of a Holborn-Kurlbaum Optical Pyrometer the following precautions should be heeded:

(a) The sources whose temperatures are sought should be backgrounds for the filament of the comparison lamp.

(b) A single comparison lamp should be used throughout a determination.

(c) The angles at the comparison lamp subtended by the aperture of the objective lens and by the aperture of the eye lens should be constant.

(d) The apparatus should be so adjusted that there is axial symmetry.

(e) The resolving power of the eyepiece should not be so great as not to permit the disappearance of the tip of the filament against the bright background image.

(f) The image of the background should be large in comparison with the comparison lamp filament.

Exp. 10. Determination of the Melting Point of a Very Small Specimen of a Substance

THEORY OF THE EXPERIMENT. — Read Arts. (40–43), 48. The object of this experiment is to determine the melting point of a specimen no larger than the head of a pin. The specimen is placed on a strip of sheet platinum which can be heated to incandescence by an electric current. When the platinum strip attains the temperature at which the substance melts, the edges of the specimen will become rounded. This may be observed by a microscope. The temperature of the strip at that moment can be conveniently obtained by means of a Holborn-Kurlbaum pyrometer.

Instead of using a microscope and separate pyrometer, one can

employ a single microscope-pyrometer which consists of a low power compound microscope provided with a small incandescent lamp in the focal plane of the ocular.

The result of the observation is the melting point K_λ according to the absolute black-body temperature scale. From this value, the thermodynamic temperature T can be computed from the equation (44),

$$\frac{1}{T} = \frac{1}{K_\lambda} + \frac{\lambda \log a}{6237}.$$

Where a is the absorptive power of platinum which for $\lambda = 0.65\,\mu$ equals 0.34.

The manipulation of this experiment is so obvious that it need not be here elaborated.

Exp. 11. The Determination of the Relation between the Luminous Intensity and the Temperature of an Incandescent Lamp Filament

THEORY OF THE EXPERIMENT. — Read Arts. 40, 42, 48, and 50. The luminous intensity of any body emitting light due to thermal causes increases rapidly with increase of temperature. For all black-bodies the luminous intensity per unit area at a given temperature is the same. But at a given temperature, the luminous intensities of various nonblack-bodies may differ within wide limits. It is therefore important to know the luminous intensities of various light sources at different temperatures. The object of this experiment is to construct a curve showing the relation between the luminous intensity and the black-body temperature of an incandescent lamp filament.

MANIPULATION. — This experiment requires (a), the determination of the temperatures of the lamp filament when operated with various currents, and (b), the determination of the candle powers of the lamp filament when operated with various currents.

For the temperature determination the Holborn-Kurlbaum method is best suited. The pyrometer employed consists of a two lens astronomical telescope, OE, Figs. 70 and 71, with a

small 8-volt comparison lamp, *C*, in the focal plane common to the two lenses. Approximately monochromatic light is produced by means of a red filter glass between the comparison lamp and the eye of the observer.
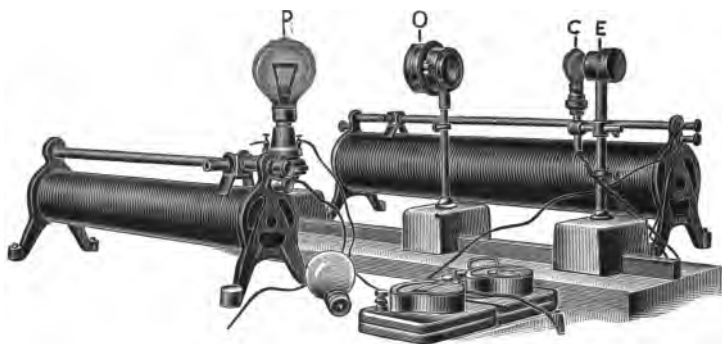

FIG. 70.

In Fig. 71, the standardized pyrometer lamp *P* and ammeter *A* are shown in series with a circuit consisting of a battery *B*, variable rheostat *R*, and switch *S*. In the common focal plane of the objective *O* and the eyelens *E*, is the comparison lamp *C*.
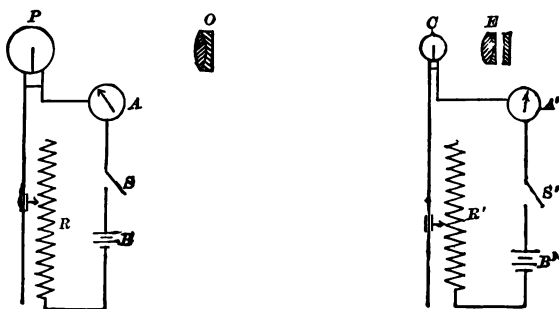

FIG. 71.

This is connected in series with a battery *B'*, ammeter *A'*, variable rheostat *R'*, and switch *S'*.

Adjust the position of the eyelens relative to the comparison lamp till a sharp image of the tip of the filament is seen in the center of the field of view. The eyelens and comparison lamp

should be now clamped in order that throughout the remainder of the experiment their position may be unaltered.

Adjust the position of the pyrometer lamp and objective till an image of the pyrometer lamp ribbon wider than the comparison lamp filament is formed in the plane of the comparison lamp filament. When the image of the pyrometer lamp ribbon is in the plane of the comparison lamp filament, there will appear to be no motion of one relative to the other on moving the eye to the right and left in front of the eyelens.

Adjust the current in the pyrometer lamp to about 3 amperes. Adjust the current in the comparison lamp till the tip of the filament is of the same brightness as the pyrometer lamp ribbon. Note the current in the comparison lamp and the current in the pyrometer lamp ribbon. Make a series of such readings at intervals of one ampere up to 10 amperes. From these data, construct the empirical calibration curve coordinating the temperature of the pyrometer ribbon and the current in the comparison lamp.

From three points on this empirical curve, not less than 300° apart, compute the three constants in (64). By means of the definite equation thereby obtained, compute the current in the comparison lamp corresponding to not less than five different temperatures of the source up to 1700° C. Plot these computed values on the sheet with the empirical curve. A curve drawn through these points should closely approximate the empirical curve. The pyrometer is now calibrated by two methods.

Within the range of this calibration, the temperatures of the incandescent lamp to be studied can now be determined. Substitute the lamp to be tested for the pyrometer lamp. For most commercial lamps the electromotive force required will be so much greater than the value required for the pyrometer lamp that the lamp to be tested must be joined in series with a storage battery of higher electromotive force. Observe a series of values of temperatures and currents of the lamp under investigation at intervals of 0.05 ampere from 0.3 ampere to normal current. Plot these values in a curve.

To determine the candle power of the lamp under test when operated at various currents, this lamp is placed at one end of a photometer bar, at the other end of the bar is placed an incandescent lamp for which the candle power is known for various current values. Each lamp is in series with a storage battery, variable rheostat and ammeter, Fig. 72.

Adjust the current in the test lamp to the value corresponding to a temperature of 700° C. Adjust the current in the standard
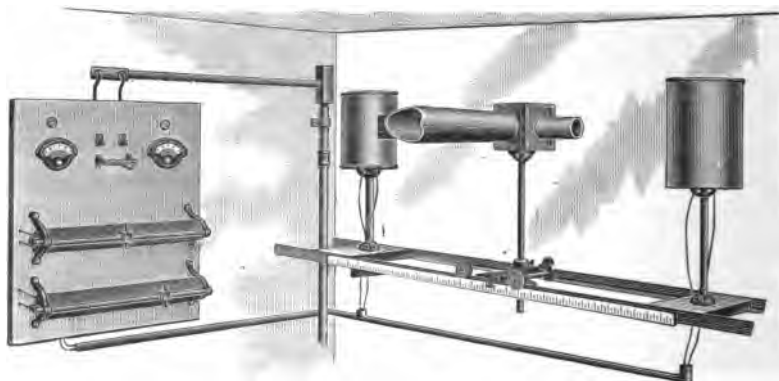

FIG. 72.

lamp till the colors of the two sources, as seen on the photometer screen are apparently the same. Move the photometer screen back and forth till the two halves of the field of view are equally bright. Note the reading on the scale of the photometer bar, and the current in each lamp.

In the same manner take a series of readings, at 0.05-ampere intervals, up to the normal current.

The candle power of the standard is obtainable from the previously obtained "current-candle power" calibration curve. The candle power of the test lamp is computed by means of the ordinary law of photometry,

$$\frac{I_1}{I_2} = \frac{r_1^2}{r_2^2}, \tag{72}$$

where I_1 and I_2 represent the luminous intensities of the two lamps and r_1 and r_2 the distances from the photometer screen

to the two lamps, respectively, when the two halves of the screen are equally bright.

Tabulate the data obtained from this part of the experiment as follows:

i_t	i_s	r_t	r_s	I_t	I_s	t

In this table i_t represents the current operating the test lamp; r_t, the distance of the photometer screen from the test lamp when both halves of the screen are equally bright; I_t, the candle power of the test lamp; t, the centigrade temperature of the test lamp. Similar quantities referring to the standard lamp are designated by the subscript s. The quantities in the last column are obtainable from the "temperature-current" curve previously constructed.

Construct a curve coordinating the candle power I_t and the temperature t of the lamp under investigation.

Exp. 12. Calibration of a Féry Absorption Pyrometer

THEORY OF THE EXPERIMENT. — Read Arts. (39–42), 46. For a description of the instrument see Art. 46. Denote the absorption per unit thickness of the glass composing the wedges by the symbol a, the thickness of the part of the wedges traversed by light from the source by the symbol x, the rate with which energy of wave-length λ is incident on the objective by the symbol J_λ, and the rate with which energy of wave-length λ emerges from the absorbing wedges by J_λ'. Then we may write:

$$J_\lambda = a^x J_\lambda'.$$

Representing by I_λ the rate with which radiance of wave-length λ leaves unit area of the source, we may write when the objective subtends at the image a constant angle,

$$I_\lambda = z J_\lambda,$$

where z is a constant of proportionality.

Whence $\qquad I_\lambda = (zJ_\lambda') \, a^* = ba^*,$

where b represents the constant quantity within the parenthesis. If Wien's Distribution Law (39) is applicable,

$$\log I_\lambda\left[= C_1 - \frac{C_2}{K_\lambda}\right] = \log b + x \log a,$$

or,

$$\left(\frac{C_1 - \log b}{\log a}\right) - x = \left[\frac{C_2}{\log a}\right]\frac{1}{K_\lambda},$$

which may be put into the form

$$c - x = \frac{d}{K_\lambda},$$

where c represents the constant quantity within the parenthesis and d the quantity within the bracket. Clearing of fractions and changing signs, the relation between x and K_λ when there is no absorptive glass in front of the wedges is seen to be:

$$K_\lambda \, (x - c) = -d. \tag{73}$$

The two constants in this equation can be determined if the wedge thickness x, corresponding to two absolute temperatures are known. From the definite equation thereby obtained, we can compute values of K_λ corresponding to a series of values of x, and from these values of K_λ and x construct the calibration curve of the instrument when no absorptive glass is in front of the wedges.

With the absorptive glass No. 1 in front of the wedges, the corresponding formula is

$$K_\lambda \, (x - c + r_1) = -d, \tag{74}$$

and with absorptive glasses Nos. 1 and 2 in front of the wedges, the corresponding formula is

$$K_\lambda \, (x - c + r_1 + r_2) = -d. \tag{75}$$

For the solution of (74) values of x corresponding to three known temperatures must be obtained. And for the solution of (75) values of x corresponding to four known temperatures must be obtained.

The object of this experiment is to construct the calibration curve of a Féry Absorption Pyrometer with no absorptive glass in front of the wedges. This curve is to be obtained by the step-by-step method and also by computation from two experimentally determined points.

MANIPULATION. — The lamp is to be filled with pure amyl acetate and the flame allowed to burn for a few minutes before beginning observations. The wick is to be adjusted so that the tip of the flame is maintained at the top of the slit in the chimney. Adjust the eyepiece of the telescope till the illuminated oval patch of light due to the lamp is distinct. By means of the rack and pinion focalize the telescope on the septum within a "black-body." See that the red glass filter is in place in the eyepiece. If the various glass surfaces are not free of dirt and moisture they are to be carefully cleaned.

Beginning when the "black-body" is at about 900° C. take a series of readings at 25° intervals, of the wedge thickness required to bring the two parts of the field of view to equal brightness. From these readings construct the empirical step-by-step calibration curve of the instrument.

From the coordinates of two points of this curve, as far apart as convenient, compute the constants in (73).

Substitute in the definite equation thereby obtained, $x = 0$, $x = 10$, $x = 20$, etc., $x = 90$, and compute the corresponding values of K_λ.

On the same sheet with the step-by-step calibration curve, construct the calibration curve obtained from these values.

Exp. 13. Calibration of a Color Identity Optical Pyrometer

THEORY OF THE EXPERIMENT. — Read Art. 44. The Color Identity Method of measuring temperatures depends upon the fact that black or gray bodies are at the same thermodynamic temperature when the light radiated from them is of the same color. The method requires, (a) a comparison source of known temperature that can be varied within wide limits, (b) some

means by which a spot of light from the source whose temperature is sought and one from the comparison source can be brought to equal brightness, (c) a device that will give sharp indications of small color differences.

The most satisfactory comparison source is a wide carbon filament incandescent lamp. The relation between the current i and the thermodynamic temperature t, expressed according to the centigrade scale, is given by (64)

$$i = a + bt + ct^2, \tag{64'}$$

where a, b, and c are three constants for a particular filament, but different for different filaments.

In the instrument designed in Purdue University, Fig. 73, light from the source whose temperature is sought is reduced to the
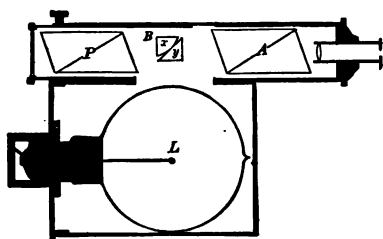

Fig. 73.

brightness of light from the comparison source L, by means of two Nicol prisms P and A. The color of light from the two sources is compared by means of a Lummer-Brodhun photometer screen B. This consists of two right-angled prisms x and y, Fig. 73. The hypothenuse face of each prism is ground to opacity except for a central polished round spot. The transparent spot on x is smaller than that on y. Light from the left incident upon the small polished spot will be transmitted, whereas that incident on the ground portion of the hypothenuse face will be reflected to one side. Light from below incident on the central part of the hypothenuse face of y will go through both prisms, whereas that incident between the edge of the small spot and the edge of the large spot will be reflected to the right. On looking through the eyepiece focalized on the center of the hypothenuse faces, one sees a central round patch of light from the source whose temperature is sought, surrounded by a ring of light from the comparison source. When the two patches are equally bright, small differences of color are readily distinguished.

MANIPULATION. — Direct the instrument into a "black-body" provided with a standardized thermoelectric pyrometer. In order to exclude extraneous light a tube blackened on the inside should connect the pyrometer and the end of the "black-body." Rotate one of the Nicol prisms and adjust the current in the comparison lamp till the two parts of the field of view are equally bright and of the same color. Note the current in the comparison lamp and the temperature of the "black-body." In the same manner take readings of the current for a series of temperatures at 100° intervals throughout the range of the "black-body." With temperatures as abscissas and currents as ordinates, plot the step-by-step calibration curve of the instrument.

From the coordinates of three points of this curve as far apart as convenient, compute the constants in (64'), and write the definite equation of the calibration curve. By substituting in this equation various convenient values for t, compute a series of values of i. On the same sheet with the empirical curve, plot this computed curve.

After the color identity optical pyrometer has been calibrated, it can be used to measure thermodynamic temperatures of gray as well as of black-bodies. The equality of brightness optical pyrometer as well as all radiation pyrometers indicate thermodynamic temperatures of black-bodies only.

Exp. 14. The Measurement of Actual Temperatures of a Gray Body

THEORY OF THE EXPERIMENT. — Read Arts. 40, 49 and Theory of Exp. 8. A gray body has been defined as one which radiates with constant emissive power for all wave-lengths. Then if the energy of wave-length λ, radiated by a black-body at absolute thermodynamic temperature T, is given by Wien's Law (37),

$$I_\lambda = c_1 \lambda^{-5} e^{-\frac{c_2}{\lambda T}},$$

the energy of wave-length λ radiated by a gray body at the same temperature is

$$I_\lambda' = a I_\lambda = a c_1 \lambda^{-5} e^{-\frac{c_2}{\lambda T}} = c_1 \lambda^{-5} e^{-\frac{c_2}{\lambda K}},$$

where a is the emissive power which is constant for all values of λ and K is the black-body temperature of the gray body.

Putting these equations in the logarithmic form we get (Art. 40),

$$\log I_\lambda = C_1 - \frac{C_2}{T}, \qquad (76)$$

$$\log I_\lambda' = \log a + C_1 - \frac{C_2}{T} = C_1 - \frac{C_2}{K}. \qquad (77)$$

Let the gray body be kept at a constant temperature and be used as the comparison source in a Wanner Optical Pyrometer. Also let the radiation from a black-body at various temperatures and of various wave-lengths be compared with that of the gray body kept at constant temperature.

Then for any wave-length λ (60),

$$\frac{I_\lambda}{I_\lambda'} = \tan^2 \theta \qquad (78)$$

where θ is the angle read from the instrument. This in logarithmic form is

$$\log I_\lambda = \log I_\lambda' + \log \tan^2 \theta = C'' + \log \tan^2 \theta.$$

If this value of $\log I_\lambda$ be substituted in (76), we have

$$\log \tan^2 \theta = C_1 - C'' - \frac{C_2}{T},$$

or, $$\log \tan^2 \theta = C_3 - C_2 \cdot \frac{1}{T}.$$

This equation shows that the relation between the reciprocal of the absolute thermodynamic temperature of the black-body and the reading of the instrument is linear, and when plotted will give a straight line. Also since (78),

$$\frac{I_\lambda}{I_\lambda'} \left[= \frac{1}{a} \right] = \tan^2 \theta,$$

when the black-body and the gray body are at the same temperature, the curves coordinating $\frac{1}{T}$ and $\log \tan^2 \theta$ for various

wave-lengths must pass through a common point. The coordinate $\frac{1}{T}$ of this point gives the actual temperature of the gray body.

If the comparison body does not radiate as a gray body the curves may not meet in a common point and its actual temperature cannot be determined in this way.

From (77),
$$\log a = C_2\left(\frac{1}{T} - \frac{1}{K}\right),$$

or, since (40)
$$C_2 = \frac{6297}{\lambda},$$

$$\log a = \frac{6297}{\lambda}\left(\frac{1}{T} - \frac{1}{K}\right). \tag{79}$$

Again, if we measure the black-body temperature of the gray body, and have the actual temperature by the method outlined above, (79) gives a means of determining the emissive power of the gray body.

There are many substances which radiate as gray bodies within the visible portion of the spectrum and within certain temperature ranges. The materials used as filaments of some incandescent lamps are among these. The object of this experiment is to determine actual temperatures of the filament of an incandescent lamp for various current values.

MANIPULATION. — In some Wanner Optical Pyrometers used for rather low temperatures, approximately monochromatic light is obtained by the use of a collimating lens of red glass instead of by the use of the prism. If this red glass lens be replaced by one of clear glass, the instrument will be adapted to making the measurements required in this experiment. Monochromatic light may be obtained by the use of colored filter glasses.

Heat a tube furnace which is to serve as a "black-body" until the temperature has become constant. The temperature of the "black-body" must be determined by means of a standard thermocouple or other means. Direct the Wanner pyrometer toward the furnace. Set the current in the comparison lamp at some

convenient value and read the position of the pointer when the analyzer is set for equal brightness, using in turn at least three differently colored filter glasses.

Repeat this for several different values of current through the comparison lamp, keeping the temperature of the "black-body" constant.

Then change the temperature of the "black-body" to some other constant value, and take another series of readings for the same series of current values above.

Repeat for a third temperature of the "black-body."

Plot the curves between $\dfrac{1}{T}$ and log tan^2 θ and obtain the values of the actual temperatures of the comparison lamp filament for the various currents.

Plot a curve between actual temperatures of the lamp and current through it.

It is not necessary to use a "black-body" for every measurement. The "black-body" can be replaced by an incandescent lamp which radiates as a gray body, if the curve between current and actual thermodynamic temperature is known for this lamp. Thus, the lamp used as a comparison lamp in the Wanner pyrometer could be calibrated by comparison with a "black-body" and then used instead of the "black-body" in subsequent measurements. When thus calibrated, the Wanner pyrometer may be used for measuring actual temperatures of gray bodies. In this case the complement of the angle read on the instrument must be taken.

CONCLUSION

51. The Selection of Pyrometers for Particular Purposes. — Of all temperature-measuring instruments the mercury-in-glass thermometer is the simplest to use and is employed wherever possible. When the tube above the mercury is filled with a gas under pressure to prevent boiling of the mercury, such thermometers can be used up to 550° C. The instrument is subject to variation when used long at the higher temperatures and

should be occasionally checked against known melting points. The indications give thermodynamic or real temperatures.

Second only to the mercury-in-glass thermometer, the thermoelectric pyrometer is most often used. The base metal thermoelectric pyrometer is available for temperatures up to about 1200° C., and the rhodioplatinum thermoelectric for short intervals of time up to 1500° C. Thermoelectric pyrometers can be used in connection with recorders. The indications give thermodynamic or real temperatures.

The resistance pyrometer is available for temperatures up to 900° C. and is capable of greater precision than any other pyrometer. It indicates real temperatures and can be used in connection with recorders. It is not so robust and is not so simple to use as the thermoelectric pyrometer.

There is no limit to the upper temperature for which radiation and optical pyrometers can be employed. The lower limit is different for different types of instrument. When the body whose temperature is sought is within a uniformly heated enclosure, the indications of a radiation or an optical pyrometer represent true temperatures; otherwise, the indications give not real temperatures, but black-body temperatures. Unless the emissivity of the surface of the hot body is known, it is impossible to translate black-body or apparent temperatures into thermodynamic or real temperatures. For this reason, radiation and optical pyrometers are used only when the instrument depending upon other principles cannot be employed. But where the body whose temperature is sought is inaccessible or too high in temperature for the other methods, recourse must be had to radiation or optical methods.

The Thwing and Foster radiation pyrometers can be used as low as 400° C., and the Féry Mirror Radiation Pyrometer as low as 500° C. These instruments can be used in connection with recorders.

Optical pyrometers employing a flame for the comparison light source are unsuited to places where there are drafts or air currents. The most commonly used optical pyrometers are of either

the polarizing type (Wanner or Scimatco), or the disappearing filament type (Morse or Holborn-Kurlbaum). The former can be used for temperatures from about 800° C., and the latter from about 700° C. Their greatest application is in the measurement of temperatures above the limits of thermoelectric pyrometers. In using any optical pyrometer one must be careful that no light reaches the image except from the body whose temperature is sought. Care must be exercised that no polarized light enters an instrument of the polarizing type. Light *reflected* from a liquid glass or metal surface, for example, must be excluded. With instruments of the disappearing filament type, settings can be made on objects of smaller size than with instruments of the other types.

The making of a setting with an optical pyrometer involves the judgment of an observer. The indication of a radiation pyrometer is given by a millivoltmeter quite independently of an observer. A radiation pyrometer can be made to record temperature on a strip of moving paper. An optical pyrometer cannot be made to record automatically. In the hands of a careful observer, an optical pyrometer is capable of greater precision than a radiation pyrometer.

52. Illustrations of the Application of Optical and Radiation Pyrometry to some Special Cases. — An optical or a radiation pyrometer indicates thermodynamic or true temperatures only of black-bodies, that is, of uniformly heated opaque enclosures. A furnace such as is used in steel hardening is so nearly a black-body that observations made with an optical or a radiation pyrometer through a small hole in the wall will give thermodynamic temperatures very nearly. If, however, an optical or a radiation pyrometer be directed toward a stream of iron from a blast furnace, it will be the black-body temperature, instead of the true temperature, that will be obtained.

In many industrial processes, the temperatures at various stages must be definite though the actual values need not be known. In such cases it is unnecessary to attempt to produce black-body conditions. In cases, however, where the true temperature is

required, either the emissivity of the material must be known, or the pyrometer must be directed into a small hole through a uniformly heated opaque enclosure in thermal equilibrium with the body. The body whose temperature is sought may be within the enclosure, or the enclosure may be within the body.

The obvious method of determining the temperature of a furnace in which there may be smoke, flame or colored fumes, is to insert into the furnace the closed end of a refractory tube and then sight through the open end an optical or a radiation pyrometer. In many cases, however, the heat near the furnace would be too great for an observer to take observations while the tube is in the furnace. In such a case the tube could be withdrawn from the furnace, the time being noted at which the withdrawal is made, and thereafter a series of simultaneous observations taken of temperatures and time. By extrapolating this temperature-time curve to the instant that the tube was withdrawn from the furnace, the temperature at the moment of withdrawal can be inferred.*

True temperatures of the steel in an open hearth furnace, or the glass in a tank furnace, can be obtained by allowing a pure carbon crucible with perforated cover to remain within the furnace till it has attained the temperature of the surroundings, ladling some of the metal into the crucible, putting on the lid, withdrawing the crucible and noting the time of withdrawal, and thereafter taking a series of simultaneous readings of temperatures and time. By extrapolating the temperature-time curve obtained from these data to the instant that the crucible was withdrawn from the furnace, the temperature at that instant is obtained.

The temperature of a pot of glass can be obtained by sighting an optical pyrometer on a point on the inside of the pot at a distance of three or four inches above the surface of the glass.

If it be desired to determine the temperature of the clinker in a rotary cement kiln, the flames and the air supply should be stopped. When the interior is clear the pyrometer is directed toward the clinker on the rising side of the rotating kiln. On

* Burgess. — Report of Pyrometer Committee of National Research Council. Trans. Am. Inst. Mining and Metallurgical Engineers, 1919.

stopping the rotation, a mass of clinker will fall from the rising side, thereby uncovering a spot of the lining toward which the pyrometer is already pointing. The time at which the clinker falls is noted and then a series of pyrometer settings made at observed times. A curve coördinating temperature and time is made, and from this curve the temperature of the interior of the clinker at the moment the lining was uncovered can be obtained by extrapolation.*

After stopping the air supply to a Bessemer converter, the temperature of the molten steel can be determined by sighting an optical pyrometer on the metal showing at the bottom of a crack in the slag.

53. Refractory Tubes. — The sheaths used to enclose thermoelectric couples, and the sight tubes used in optical and radiation pyrometry should be made of materials of high thermal conductivity that will not soften or transfuse gases at the temperature at which they are to be used; that will not break when subjected to sudden temperature changes or ordinary mechanical shocks; and that will not be corroded by the hot materials by which they may be surrounded. At the present time the outstanding troubles in the measurement of high temperatures are due to the lack of materials possessing these properties to a sufficiently high degree.

On account of their high thermal conductivity, mechanical strength and ability to withstand sudden temperature changes, metal tubes are used wherever possible. Iron and steel can be used up to about 800° C., in places where there is little danger from corrosion. An iron tube with the surface impregnated with aluminum is less subject to oxidation than an iron tube not thus "calorized." Pure nickel also is less subject to oxidation than . iron. Chromel "A" also resists oxidation better than iron and can be used continuously at temperatures as high as 1200° C.

Fused quartz withstands sudden changes of temperature and will not soften at 1000° C. It can be used in an oxidizing atmos-

* Dana & Fairchild. — Pyrometry in Rotary Portland Cement Kilns Trans. Am. Inst. Mining and Metallurgical Engineers, 1919.

phere and in all acid fumes except hydrofluoric.   It should not be used in either alkaline or in reducing atmospheres at high temperatures.

Glazed alundum (Al_2O_3 + clay binder) and corundite (emery + clay binder) can be used up to 1400° C.

Glazed "impervite" porcelain, also called "usalite," can be used up to 1500° C., and above.   The porcelains, however, cannot be subjected to a sudden large change of temperature without breaking.   They also conduct heat slowly.

Carborundum can be used up to and above 1500° C., except in presence of chlorine and basic slags.   This material has a high thermal conductivity compared with other non-metals.   Tubes of crystallized carborundum are sold under the trade name "Silfrax."

Graphite and fireclay are the most refractory of the substances used for pyrometer tubes and sheaths.   Tubes of these materials are commonly used outside of porcelain tubes.

TABLE 1. — Boiling Point of Water under Different Barometric Pressures

(a) Temperatures in Degrees Centigrade and Pressures in Millimeters of Mercury

° C.	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
90	525.4	527.4	529.4	531.4	533.4	535.5	537.5	539.6	541.6	543.7
91	545.7	547.8	549.9	551.9	554.0	556.1	558.2	560.3	562.4	564.6
92	566.7	568.8	571.0	573.1	575.3	577.4	579.6	581.8	584.0	586.1
93	588.3	590.5	592.7	595.0	597.2	599.4	601.6	603.9	606.1	608.4
94	610.7	612.9	615.2	617.5	619.8	622.1	624.4	626.7	629.0	631.4
95	633.7	636.0	638.4	640.7	643.1	645.5	647.9	650.2	652.6	655.0
96	657.4	659.9	662.3	664.7	667.1	669.6	672.0	674.5	677.0	679.4
97	681.9	684.4	686.9	689.4	691.9	694.5	697.0	699.5	702.1	704.6
98	707.2	709.7	712.3	714.9	717.5	720.1	722.7	725.3	727.9	730.5
99	733.2	735.8	738.5	741.2	743.8	746.5	749.2	751.9	754.6	757.3
100	760.0	762.7	765.5	768.2	770.9	773.7	776.5	779.2	782.0	784.8

(b) Temperatures in Degrees Fahrenheit and Pressures in Inches of Mercury

° F.	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
194	20.68	20.73	20.77	20.82	20.86	20.90	20.95	20.99	21.04	21.08
195	21.13	21.17	21.22	21.26	21.30	21.35	21.39	21.44	21.48	21.53
196	21.58	21.62	21.67	21.71	21.76	21.80	21.85	21.89	21.94	21.99
197	22.03	22.08	22.12	22.17	22.22	22.26	22.31	22.36	22.40	22.45
198	22.50	22.54	22.59	22.64	22.69	22.73	22.78	22.83	22.88	22.92
199	22.97	23.02	23.07	23.11	23.16	23.21	23.26	23.31	23.36	23.40
200	23.45	23.50	23.55	23.60	23.65	23.70	23.75	23.80	23.85	23.89
201	23.94	23.99	24.04	24.09	24.14	24.19	24.24	24.29	24.34	24.39
202	24.44	24.49	24.54	24.59	24.64	24.69	24.74	24.80	24.85	24.90
203	24.95	25.00	25.05	25.10	25.15	25.21	25.26	25.31	25.36	25.41
204	25.46	25.52	25.57	25.62	25.67	25.73	25.78	25.83	25.88	25.94
205	25.99	26.04	26.10	26.15	26.20	26.25	26.31	26.36	26.42	26.47
206	26.52	26.58	26.63	26.68	26.74	26.79	26.85	26.90	26.96	27.01
207	27.07	27.12	27.18	27.23	27.29	27.34	27.40	27.45	27.51	27.56
208	27.62	27.67	27.73	27.79	27.84	27.90	27.95	28.01	28.07	28.12
209	28.18	28.24	28.29	28.35	28.41	28.46	28.52	28.58	28.64	28.69
210	28.75	28.81	28.87	28.92	28.98	29.04	29.10	29.16	29.21	29.27
211	29.33	29.39	29.45	29.51	29.57	29.62	29.68	29.74	29.80	29.86
212	29.92	29.98	30.04	30.10	30.16	30.22	30.28	30.34	30.40	30.46

TABLE 2. — Corrections for the Influence of Gravity on the Height of the Barometer

(a) Reduction to Latitude 45°

From 0° to 45° the corrections are subtractive; from 45° to 90° the corrections are additive.

Lat.	Barometric height in mm. reduced to 0° C.												Lat.
	670	680	690	700	710	720	730	740	750	760	770	780	
Deg.	mm.	mm.	mm.	mm.	mm.	mm.	mm.	mm.	mm.	mm.	mm.	mm.	Deg.
0	1.74	1.76	1.79	1.81	1.84	1.86	1.89	1.92	1.94	1.97	1.99	2.02	90
5	1.71	1.73	1.76	1.79	1.81	1.84	1.86	1.89	1.91	1.94	1.96	1.99	85
10	1.63	1.65	1.68	1.70	1.73	1.75	1.78	1.80	1.83	1.85	1.87	1.90	80
15	1.50	1.53	1.55	1.57	1.59	1.61	1.64	1.66	1.68	1.70	1.73	1.75	75
20	1.33	1.35	1.37	1.39	1.41	1.43	1.45	1.47	1.49	1.51	1.53	1.55	70
25	1.12	1.13	1.15	1.17	1.18	1.20	1.22	1.23	1.25	1.27	1.28	1.30	65
30	0.87	0.88	0.89	0.91	0.92	0.93	0.95	0.96	0.97	0.98	0.00	0.01	60
35	0.59	0.60	0.61	0.62	0.63	0.64	0.65	0.66	0.66	0.67	0.68	0.69	55
40	0.30	0.31	0.31	0.31	0.32	0.32	0.33	0.33	0.34	0.34	0.35	0.35	50
45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	45

(b) Reduction to Sea Level

Corrections are subtractive.

Elevation.	Barometric height in mm. reduced to 0° C.						
	660	680	700	720	740	760	770
m.	mm.	mm.	mm.	mm.	mm.	mm.	mm.
100			0.01	0.01	0.01	0.01	0.02
200		0.03	0.03	0.03	0.03	0.03	0.03
300		0.04	0.04	0.04	0.04	0.04	
400	0.05	0.05	0.05	0.06	0.06	0.06	
500	0.06	0.07	0.07	0.07	0.07	0.07	
600	0.08	0.08	0.08	0.08	0.09		
700	0.09	0.09	0.10	0.10	0.10		
300	0.10	0.11	0.11	0.11	0.12		
900	0.12	0.12	0.12	0.13			
1900	0.13	0.13	0.14	0.14			

TABLE 3.—Values of log (tan² θ) for Use with the Wanner Optical Pyrometer

θ	log (tan² θ)	θ	log (tan² θ)	θ	log (tan² θ)
Deg.		Deg.		Deg.	
10	−1.50736	34	−0.34202	58	0.40842
11	−1.42270	35	−0.30954	59	0.44246
12	−1.34506	36	−0.27748	60	0.47712
13	−1.27328	37	−0.24578	61	0.51250
14	−1.20646	38	−0.21438	62	0.54866
15	−1.14390	39	−0.18326	63	0.58566
16	−1.08500	40	−0.15238	64	0.62364
17	−1.02932	41	−0.12168	65	0.66266
18	−0.97642	42	−0.09112	66	0.70284
19	−0.92606	43	−0.06068	67	0.74430
20	−0.87786	44	−0.03032	68	0.78718
21	−0.83164	45	0.00000	69 ·	0.83164
22	−0.78718	46	0.03032	70	0.87786
23	−0.74430	47	0.06068	71	0.92606
24	−0.70284	48	0.09112	72	0.97642
25	−0.66266	49	0.12168	73	1.02932
26	−0.62364 ·	50	0.15238	74	1.08500
27	−0.58566	51	0.18326	75	1.14390
28	−0.54866	52	0.21438	76	1.20646
29	−0.51250	53	0.24578	77	1.27328
30	−0.47712	54	0.27748	78	1.34506
31	−0.44246	55	0.30954	79	1.42270
32	−0.40842	56	0.34202	80	1.50736
33	−0.37496	57	0.37496		

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